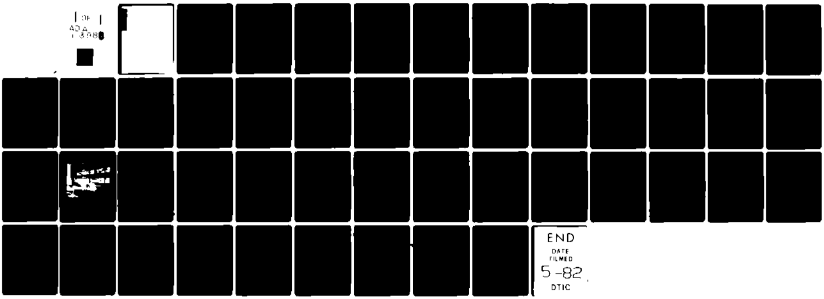
AD-A113 988 ARMY RESEARCH AND TECHNOLOGY LABS HAMPTON VA STRUCTU--ETC F/6 1/3
PERFORMANCE TESTING OF A MAIN ROTOR SYSTEM FOR A UTILITY HELICO--ETC(U)
APR 82 J D BERRY

UNCLASSIFIED NASA-TM-83274 NL



AD A113988

NASA
Technical Memorandum 83274

AVRADCOM
Technical Report 82-B-3

Performance Testing of a Main Rotor System for a Utility Helicopter at 1/4 Scale

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Scientific and Technical Information Branch

1982

CONTENTS

SUMMARY

Performance measurements on two rotor systems were made for hover and for simulated forward flight in the Langley 4- by 7-Meter Tunnel. The first rotor system, tested as a "baseline," was a dynamically accurate, 1/4-scale model of the current rotor system on the UH-1 helicopter. The second rotor system, designed for "advanced" performance with similar dynamics, varied from the baseline system in airfoil cross section, in twist, and in geometric taper of the planform. In hover out of ground effect, the advanced rotor demonstrated a maximum improvement of 10 percent in the figure of merit for an isolated rotor when compared to the baseline rotor. A thrust improvement of about 7 percent was shown for the helicopter (including the fuselage downloading effects) using the advanced rotor in hover out of ground effect, at a torque coefficient equivalent to full power of the full-scale vehicle at sea-level standard conditions. In forward flight, the advanced rotor demonstrated significant reductions in torque (power) required throughout the range of advance ratios (speeds) tested. Reductions of up to 17 percent in required torque were measured, with the larger reductions occurring at the higher advance ratios and higher lift values.

INTRODUCTION

Improvements in rotorcraft performance through the use of new airfoil shapes and variations in rotor twist and planform have been studied at the U.S. Army Structures Laboratory at Langley Research Center (refs. 1 and 2). Interest in acquisition by the U.S. Army of a replacement, all-composite main rotor blade for extension of the life of UH-1 utility helicopters provided a specific design goal. By distributing airfoil cross section, twist, and taper as described in reference 2, a rotor system was designed which was predicted to improve the performance of the UH-1 helicopter.

This test program compares the performance at 1/4 scale of a standard, "baseline" rotor-blade set to that of a new, "advanced" rotor-blade set. The baseline rotor blades and hub were designed to match the performance and dynamic characteristics of the full-scale UH-1 helicopter. The advanced rotor blade was designed such that performance changes would be attributed only to the geometric properties of the blades. The wind-tunnel tests were conducted at Mach scale, matching full-scale tip speeds. By matching tip speeds, full-scale Mach effects (most prominent in the tip region) are simulated at model scale. Examples of Mach-scale to full-scale performance correlation are given in references 3 and 4.

Performance data were acquired and analyzed for both baseline and advanced blade sets in hover, in and out of ground effect, and at forward speeds from 26 to 57 m/sec (50 to 110 knots; characteristic of the UH-1 helicopter). Ranges of lift and propulsive-force coefficients representing the full-scale UH-1 helicopter were tested. Acoustic data were acquired during the test and are presented in reference 5.

Since the purpose of this test was to determine the effect of geometric and not dynamic influences on performance, the use of the advanced blade system on a flight vehicle will require optimization of dynamic characteristics for the advanced blade

design. The advanced blade system tested had a significantly lower polar moment of inertia than the baseline, which would result in less energy available for entry into autorotation.

SYMBOLS

The physical quantities defined in this paper are given in the International System of Units (SI). Measurements and calculations were made in the U.S. Customary Units and conversion factors relating the two systems are presented in reference 6. The rotor performance data have been resolved in the shaft axis system with the moment reference center located at the nominal center of gravity of the vehicle. Figure 1 is an illustration of the positive directions of directed quantities.

A_1 lateral cyclic blade pitch, deg

a_0 rotor coning angle, deg

a_1 longitudinal flapping, deg (A1S in tables III and IV)

B_1 longitudinal cyclic blade pitch, deg

b_1 lateral flapping, deg (B1S in tables III and IV)

C_D rotor drag coefficient, $\text{Drag}/\rho\pi\Omega^2R^4$ (CD in tables III and IV)

C_L rotor lift coefficient, $L/\rho\pi\Omega^2R^4$ (CL in tables III and IV)

C_Q rotor-shaft torque coefficient, $Q/\rho\pi\Omega^2R^5$ (CQ in tables III and IV)

C_T rotor thrust coefficient, $T/\rho\pi\Omega^2R^4$

C_{TF} fuselage thrust (normal force coefficient), $T_F/\rho\pi\Omega^2R^4$

C_{TT} total thrust coefficient, $(T + T_F)/\rho\pi\Omega^2R^4$

C.G. center of gravity

c local chord of rotor blade, m

D drag, N

d rotor diameter, 2R, m

FM rotor figure of merit, $0.707C_T^{3/2}/C_Q$

H height from tunnel floor to hub center, m

L rotor lift, N

MT advancing-blade tip Mach number, $(V_\infty + \Omega R)$/Local speed of sound (tables III and IV)

Q rotor torque, N-m

R	rotor radius, 1.829 m
T	rotor thrust, N
T_f	fuselage thrust (normal force), N
V_t	rotor tip speed, ΩR, m/sec
V_∞	free-stream velocity, m/sec
α_f	fuselage angle of attack, deg (ALPF in tables III and IV)
μ	rotor advance ratio, V_∞/V_t (MU in tables III and IV)
ρ	free-stream density, kg/m^3
ψ	rotor azimuth, deg
Ω	rotor angular velocity, 136 rad/sec (nominal)

MODEL AND APPARATUS

This investigation was conducted using the general rotor model system (GRMS) (as described in refs. 7 and 8) in the Langley 4- by 7-Meter Tunnel. The GRMS was configured as a 1/4-scale model of the UH-1 helicopter. A detailed sketch, an internal component layout, and a photograph of the model are presented in figures 2(a), (b), and (c), respectively.

The 1/4-scale fuselage represented a general member of the UH-1 helicopter family, without precise modeling of specific helicopter details such as doors or external stores; thus, the model represents a "cleaner" body configuration than an actual helicopter. The hub system used for this study was the teetering-rotor hub system for the UH-1 helicopter, including leading pitch horns with no pitch-flap coupling. Hub precone, pitch-horn offset, and teetering-axis/feathering-axis offset (undersling) are properly scaled. The swept area of the pitch links and the shaft are larger than scale, but no stabilizer bar is modeled, resulting in similar hub drag area.

A set of blades closely scaled both geometrically and dynamically to represent the 14.6-m (48-ft) main rotor system of the UH-1 helicopter was tested as a baseline. The baseline blade is of uniform NACA 0012 airfoil cross section. Twist from center of rotation to tip varies linearly by -10.9°. The dynamic characteristics of the baseline rotor system were designed to match those of the full-scale UH-1 helicopter rotor system. The analysis in reference 9 was used to verify that the natural modes of the baseline blade set matched those of the full-scale UH-1 helicopter blades. The dynamic properties of the baseline blade set, when coupled with the stiff control system of the GRMS, were predicted to result in undesirable response characteristics. Therefore, variable-stiffness pitch links were used to soften the control system, avoiding unfavorable system response.

The advanced blades were designed as a bolt-on replacement for the standard blade set. The advanced blade is of the same overall radius R as the baseline. The inboard chord of the advanced blade is 26 percent greater than the baseline and constant to 0.5R. The chord has a three-to-one taper ratio from 0.5R to the tip.

The airfoil sections used are described in reference 1. From root to 0.8R, a RC(3)-12 section (ref. 1) is used; between 0.8 and 0.9R, there is a transition to a RC(3)-10 section, and the transition continues to a RC(3)-08 section at the tip. The chord line twists linearly from the center of rotation to the tip by -14°. The advanced design rotor system was constructed to have dynamic characteristics similar to the baseline system. Geometric differences, particularly in the tip region, prevented matching dynamic characteristics exactly.

Both blade types tested are shown in the planforms in figure 3. Table I is a summary of the characteristics of both rotor systems tested. Although the advanced blade set has a higher (by 4.8 percent) planform solidity, the solidity factors affecting performance (thrust- and torque-weighted solidities from ref. 10) are lower (by 18.9 percent and 25.6 percent, respectively) because of the taper. A portion of the performance differences measured may have been attributed to surface-condition differences between the two blade sets, which were supplied from different sources. Although both blade sets met specifications for surface finish, the finish on the advanced set was smoother.

TEST ANᴦ PROCEDURES

The performance of the advanced and baseline blade systems was investigated at the nominal rotational speed (1296 rpm) in hover, in and out of ground effect, and in simulated forward flight at advance ratios simulating speeds up to 57 m/sec (110 knots). Hover testing was conducted in the wind-tunnel test section with the ceiling and walls of the test section fully raised and the tunnel circuit closed to prevent rotor-induced crossflow. Hover testing out of ground effect was conducted at a height-to-diameter ratio (H/d) of 1.3. To determine ground proximity effects, H/d was varied using the model support system. The minimum advance ratio (0.10) was established using the criteria of references 11 and 12 to prevent flow breakdown and to minimize the correction for flow angularity, respectively. For forward flight, the test-section ceiling and solid walls were in their normal closed configuration and the rotor H/d was held at 0.67 to minimize flow interference due to the presence of the test-section floor and ceiling. The ratio of rotor diameter to test-section width was 0.55, and the ratio of rotor disk area to test-section cross section was 0.35. The data presented have been corrected for these influences by the methods of reference 11.

Performance in forward flight was determined by setting a fuselage angle of attack and holding a rotor propulsive force constant through the input of various longitudinal cyclic values for a range of lift values determined by collective setting of blade pitch. The values of rotor propulsive force were chosen to offset nominal values of fuselage drag determined from reference 13. At selected combinations of advance ratio and fuselage angle of attack, an additional value of propulsive force was tested to determine the sensitivity of rotor power to rotor drag (propulsive force). Lateral cyclic blade pitch was held close to a value of -1.2° which was chosen as a result of analysis of full-scale data. Mach number differences of up to 0.01 were caused by variations in temperature. Forward-flight test conditions are listed in table II.

RESULTS AND DISCUSSION

Hover

Rotor performance out of ground effect is shown in figure 4 for both blade systems. The thrust coefficient (C_T) of 0.0033 is required to offset the design gross weight of the UH-1 helicopter (42.2 kN (9500 lb)), at sea-level standard conditions. A thrust coefficient of 0.0039 was obtained out of ground effect with the baseline blade system at the maximum power available from the model system. The advanced blade system was tested to a maximum thrust coefficient of 0.0043 without using all of the available system power.

The figure of merit of the advanced blade system reached a maximum of 0.76 versus the maximum of 0.69 for the baseline blade system, which represents a 10 percent improvement at $C_T = 0.0038$. The advanced blade system reached a maximum efficiency at a C_T of about 0.004 where the baseline blade system did not have a maximum value within the range tested.

At the lowest thrust value (well below useful lifting thrust), the advanced blade system experienced a torque rise. This torque rise can result from the higher twist of the advanced blade, since higher twist increases the elemental induced power with offsetting inboard and outboard thrusts when the total thrust approaches zero. A qualitative measure of required system power is provided by the motor temperature. Testing the baseline blades at maximum thrust caused the temperatures of the electric drive motor to rise severely, but when testing the advanced blades, the extreme temperatures were not encountered. It should be noted that no loss of balance accuracy is caused by a high motor temperature.

Full-scale data of reference 14 taken on a hover test stand are also shown in figure 4. Agreement is shown between the baseline data and full-scale data. The full-scale data were taken at $H/d = 0.875$ (not completely out of ground effect) for the isolated rotor, while the model data were taken completely out of ground effect but with small thrust recovery due to the presence of the fuselage. These effects tend to be offsetting. This correlation provides confidence in the prediction of the advanced-rotor hover performance at full scale.

The effect of the rotor downwash on the fuselage is shown in figure 5. Fuselage and total thrust coefficients are presented as functions of torque coefficient. By design, the thrust distribution in the advanced-rotor disk is such that more rotor lift (and related downwash) is distributed inboard. The advanced blade system did require additional thrust coefficient of 0.00003 in hover because of fuselage downloading (about 1 percent difference in total thrust). When this additional download is subtracted from rotor thrust, an increase of 7 percent total thrust (equivalent full-scale additional lifting thrust of 3.1 kN (700 lb)) is realized at full power of the UH-1 helicopter (torque coefficient of 0.00021) out of ground effect.

Presented in figure 6 are changes due to effects of ground proximity. The rotor figure of merit and the fuselage thrust (normal force) coefficient are shown at a nominal rotor thrust coefficient of 0.003. Contact of the support system with the test-section floor prevented testing to the "skids-on-the-ground" condition which occurs at $H/d = 0.304$. The figure of merit shows less sensitivity to ground proximity for the advanced blade system than for the baseline system in the range tested.

Forward Flight

The basic performance data taken in forward flight are presented in table III for the baseline blade and in table IV for the advanced blade. Comparisons between the two blade systems at the same fuselage angle and advance ratio are shown in figure 7, which is referenced in table II.

The data show differences in required torque, with baseline blade system requiring more torque than the advanced blade system. The baseline data shown in figure 7(a) were obtained without trimming the rotor attitude, through cyclic control input, for constant propulsive force. All other data shown in figure 7 were taken with propulsive force held nearly constant. Since the hub drag area of the system tested closely matches that of the full-scale helicopter, no correction for hub drag has been applied to the forward-flight data.

Rotor performance data for one schedule of conditions are presented in figure 8 as a function of advance ratio. This schedule represents nominal flight conditions of the UH-1 helicopter. Rotor torque data are presented at three lift-coefficient values (0.0025, 0.0030, and 0.0035). At the lowest advance ratio (0.10) and at the lowest lift-coefficient level (0.0025), a difference of 0.000015 in torque coefficient is observed. The torque difference, when scaled, amounts to a full-scale power decrement of 47 kW (63 hp) at sea-level standard conditions. At the same advance ratio with a higher lift coefficient (0.0035), a difference of 0.000022 in torque coefficient, or 69 kW (93 hp) full-scale power, is observed. At a high advance ratio (0.20) and the lowest lift coefficient (0.0025), the decrement in the torque coefficient is 0.000016, or 50 kW (68 hp) full-scale power. A higher lift coefficient (0.0035) at the same advance ratio, yields a torque decrement of 0.000031, or 98 kW (131 hp) full-scale power. At the highest advance ratio tested (0.22) with $C_L = 0.0035$, the power decrement amounts to a decrease of over 17 percent in the power required by the baseline blade set. Increases in power differences were observed with increases in lift coefficient at all advance ratios tested and with increasing advance ratio at all levels of lift coefficient tested.

CONCLUDING REMARKS

A 1/4-scale model of an advanced rotor blade for the UH-1 helicopter was tested to determine its performance characteristics. Wind-tunnel tests were conducted in hover and forward flight with baseline and advanced blade sets which were dynamically similar. Through the use of advanced airfoils and geometric variations in rotor blades, significant rotor performance improvements were measured. When compared to the baseline blades tested, the advanced blade system showed the following:

1. The maximum rotor figure of merit was 10 percent higher.

2. When fuselage download was included, the thrust available for hover out of ground effect was about 7 percent greater at a torque coefficient equivalent to full power available in the UH-1 helicopter at sea-level standard conditions.

3. Power reductions of up to 17 percent were measured in forward flight. The higher power savings were measured at higher lift coefficients and higher advance ratios.

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March 24, 1982

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TABLE I.- CHARACTERISTICS OF ROTOR SYSTEMS

	Standard	Advanced
Twist (linear)	-10.9	-14.0
Solidity:		
Planform	0.0464	0.0486
Thrust weighted	0.0464	0.0376
Torque weighted	0.0464	0.0345
Natural frequencies/revolution:		
Collective mode:		
First beam	0.248	0.247
First chord	0.424	0.490
First torsion	3.661	3.269
Scissors mode:		
First beam	1.117	1.224
First chord	1.622	2.202
First torsion	(a)	6.168
Cyclic mode:		
Second beam	2.735	2.713
Second chord	1.463	1.776
First torsion	3.659	3.269

[a]Not predicted.

TABLE II.- TEST CONDITIONS FOR FORWARD FLIGHT

Figure 7	Baseline rotor system			Advanced rotor system		
	μ	α_f	C_D	μ	α_f	C_D
(a)	0.103	Varies	-0.00008	0.102	-0.32	-0.00008
(b)	.103	2.16	-.00008	.103	2.16	-.00008
(c)	.102	4.64	-.00008	.102	4.67	-.00008
(d)	.143	-1.15	-.00013	.143	-1.18	-.00013
(e)	.144	1.35	-.00013	.144	1.32	-.00013
(f)	.144	3.86	-.00013	.144	3.84	-.00014
(g)	.184	-1.62	-.00020	.184	-1.58	-.00020
(h)	.184	.41	-.00018	.184	.42	-.00020
(i)	.186	.39	-.00013	.185	.44	-.00013
(j)	.185	2.01	-.00012	.185	1.89	.00013
(k)	.204	-2.08	-.00025	.203	-2.05	-.00025
(l)	.205	-.04	-.00025	.205	-.07	-.00025
(m)	.205	-.02	-.00020	.205	-.07	-.00021
(n)	.204	1.95	-.00020	.206	1.95	-.00025
(o)	.226	Varies	-.00030	.224	.19	-.00030

TABLE III.- FORWARD-FLIGHT PERFORMANCE OF BASELINE BLADE

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.000312	.000056	.000023	.106	.21	.786	-.41	-1.34
.000589	.000059	-.000004	.102	.33	.783	-.32	-1.25
.000882	.000063	-.000028	.102	.45	.783	-.40	-1.26
.001209	.000068	-.000049	.103	.58	.781	-.22	-1.19
.001526	.000076	-.000072	.103	.71	.779	-.32	-1.15
.001797	.000083	-.000091	.103	.81	.777	-.31	-1.22
.002103	.000091	-.000106	.103	.94	.778	-.22	-1.23
.002428	.000102	-.000127	.103	1.07	.776	-.32	-1.29
.002734	.000113	-.000138	.103	1.19	.777	-.17	-1.21
.003006	.000125	-.000158	.103	1.31	.779	-.28	-1.16
.003361	.000141	-.000171	.103	1.44	.776	-.23	-1.17
.003611	.000156	-.000184	.103	1.55	.778	-.26	-1.21
.001776	.000083	-.000099	.103	.83	.779	-.66	-1.33
.000304	.000057	.000016	.102	.22	.780	-.98	-1.40
.001517	.000076	-.000066	.103	2.31	.775	-1.27	-.80
.001824	.000082	-.000071	.103	2.27	.774	-.74	-.92
.002150	.000090	-.000079	.103	2.28	.773	-.45	-.93
.002474	.000098	-.000076	.103	2.19	.774	.08	-1.04
.002758	.000108	-.000081	.103	2.14	.775	.28	-1.00
.003050	.000119	-.000085	.103	2.09	.774	.47	-.97
.003393	.000135	-.000090	.103	2.06	.774	.67	-.98
.003662	.000149	-.000095	.103	2.00	.773	.83	-.99
.003823	.000157	-.000098	.103	2.04	.775	.85	-.98
.002736	.000107	-.000079	.102	2.12	.776	.34	-1.06
.001815	.000081	-.000066	.102	2.29	.776	-.61	-.90
.001513	.000075	-.000068	.102	4.77	.777	-3.68	-.72
.001841	.000081	-.000067	.102	4.78	.776	-2.87	-.77
.002110	.000089	-.000070	.102	4.67	.778	-2.51	-.93
.002421	.000096	-.000077	.102	4.57	.777	-2.17	-.95
.002735	.000107	-.000082	.102	4.62	.777	-2.01	-.84
.003027	.000118	-.000085	.102	4.55	.778	-1.71	-.81
.003326	.000132	-.000087	.102	4.52	.779	-1.53	-1.14
.003635	.000147	-.000090	.102	4.55	.778	-1.39	-.88
.003771	.000154	-.000100	.102	4.50	.777	-1.37	-.95
.002710	.000106	-.000079	.102	4.68	.778	-2.01	-.95
.001810	.000081	-.000068	.102	4.81	.780	-3.02	-.74

TABLE III.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.001511	.000091	-.000125	.144	-1.12	.808	-1.38	-.96
.001844	.000095	-.000129	.143	-1.09	.810	-.25	-1.12
.002102	.000100	-.000127	.143	-1.08	.809	.46	-1.14
.002369	.000106	-.000130	.144	-1.12	.809	1.00	-1.30
.002701	.000114	-.000129	.143	-1.20	.812	1.63	-1.25
.003016	.000124	-.000134	.143	-1.20	.811	1.89	-1.29
.003312	.000135	-.000138	.144	-1.19	.809	2.21	-1.27
.003578	.000145	-.000137	.144	-1.20	.810	2.48	-1.28
.003742	.000154	-.000139	.144	-1.24	.808	2.68	-1.33
.002643	.000113	-.000127	.143	-1.10	.812	1.49	-1.23
.001771	.000094	-.000121	.143	-1.06	.813	-.19	-1.09
.001505	.000092	-.000124	.144	1.43	.810	-3.67	-.77
.001829	.000095	-.000119	.144	1.44	.812	-2.27	-.96
.002094	.000101	-.000122	.144	1.39	.812	-1.56	-1.06
.002407	.000107	-.000123	.144	1.37	.811	-.90	-1.00
.002725	.000116	-.000131	.144	1.30	.812	-.46	-1.03
.002989	.000123	-.000124	.144	1.33	.811	-.04	-1.11
.003281	.000135	-.000132	.144	1.31	.811	.22	-1.03
.003522	.000148	-.000154	.144	1.25	.813	.23	-.91
.003745	.000156	-.000137	.144	1.26	.812	.70	-1.03
.002712	.000115	-.000125	.144	1.32	.812	-.35	-.96
.001805	.000095	-.000125	.143	1.44	.813	-2.50	-.75
.001511	.000090	-.000116	.143	4.11	.812	-6.09	-.32
.001729	.000092	-.000119	.143	3.86	.813	-5.11	-.79
.002065	.000098	-.000125	.144	3.95	.813	-4.38	-.55
.002354	.000106	-.000128	.144	3.84	.813	-3.74	-.80
.002631	.000112	-.000126	.144	3.91	.814	-3.27	-.77
.002913	.000119	-.000127	.143	3.78	.815	-2.76	-.83
.003276	.000131	-.000126	.144	3.87	.813	-2.40	-.87
.003509	.000143	-.000134	.144	3.81	.813	-2.21	-.82
.003671	.000151	-.000142	.144	3.72	.814	-2.03	-.95
.003810	.000157	-.000134	.144	3.75	.812	-1.82	-.93
.002634	.000112	-.000124	.143	3.85	.814	-3.14	-.84
.001735	.000093	-.000120	.143	3.92	.812	-5.14	-.47

TABLE III.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.001479	.000118	-.000196	.182	-1.60	.838	-5.20	-.43
.001817	.000122	-.000198	.183	-1.60	.835	-3.19	-.82
.002477	.000150	-.000237	.199	-1.53	.780	-2.10	-.86
.002374	.000133	-.000207	.183	-1.63	.836	-1.20	-.97
.002678	.000140	-.000200	.184	-1.67	.835	-.30	-1.09
.003005	.000148	-.000204	.184	-1.59	.835	.21	-1.09
.003243	.000158	-.000207	.184	-1.68	.836	.65	-1.14
.003539	.000170	-.000209	.184	-1.61	.836	1.06	-1.17
.003692	.000178	-.000202	.184	-1.58	.836	1.34	-1.27
.003831	.000186	-.000209	.184	-1.64	.837	1.58	-1.25
.002680	.000139	-.000201	.184	-1.67	.838	-.30	-1.08
.001809	.000122	-.000199	.182	-1.59	.838	-3.25	-.94
.002024	.000122	-.000179	.183	.39	.841	-3.19	-.72
.002358	.000129	-.000181	.183	.46	.841	-2.26	-.76
.002640	.000136	-.000178	.184	.39	.841	-1.41	-.95
.002958	.000145	-.000181	.184	.47	.840	-.89	-1.03
.003207	.000156	-.000190	.184	.32	.840	-.44	-1.09
.003628	.000172	-.000182	.184	.42	.840	.30	-1.09
.003697	.000178	-.000188	.184	.43	.841	.30	-1.05
.002060	.000126	-.000193	.184	1.91	.844	-4.80	-.49
.002306	.000127	-.000176	.184	1.97	.846	-3.64	-.68
.002667	.000141	-.000204	.185	2.04	.844	-3.29	-.60
.002930	.000148	-.000200	.185	2.10	.843	-2.70	-.76
.003229	.000162	-.000215	.186	1.87	.843	-2.12	-.86
.003535	.000174	-.000210	.185	1.88	.844	-1.44	-.79
.003669	.000178	-.000204	.186	1.90	.844	-1.17	-.85
.003146	.000154	-.000196	.184	1.83	.848	-1.95	-.74
.002953	.000149	-.000205	.185	1.78	.846	-2.46	-.87

TABLE III.- Continued

CL	CQ	CD	MU	ALPF	MT	AIS	BIS
.002073	.000112	-.000122	.183	.37	.843	-1.63	-.83
.002373	.000119	-.000124	.184	.43	.844	-1.01	-.98
.002574	.000122	-.000118	.184	.36	.844	-.39	-1.05
.002965	.000131	-.000121	.184	.44	.843	.13	-1.07
.003207	.000144	-.000132	.184	.38	.843	.41	-1.04
.003523	.000156	-.000127	.184	.46	.843	.86	-1.14
.004282	.000190	-.000150	.200	.48	.787	.96	-1.11
.003506	.000156	-.000130	.184	.36	.845	.89	-1.14
.003177	.000140	-.000124	.184	.24	.845	.60	-1.06
.002909	.000129	-.000112	.184	.39	.844	.26	-1.06
.002034	.000113	-.000124	.184	2.00	.846	-3.28	-.67
.002362	.000118	-.000121	.184	2.06	.846	-2.45	-.78
.002611	.000125	-.000121	.185	2.12	.845	-1.96	-1.02
.002906	.000133	-.000124	.185	2.19	.845	-1.54	-.90
.003173	.000143	-.000127	.185	1.92	.846	-.89	-1.06
.003475	.000156	-.000131	.185	1.98	.846	-.54	-.99
.003615	.000163	-.000128	.185	2.02	.846	-.31	-.98
.003189	.000142	-.000126	.185	1.93	.847	-.85	-.85
.002847	.000131	-.000116	.184	1.86	.848	-1.17	-.96
.001463	.000115	-.000114	.203	-2.06	.850	-2.70	-1.12
.001851	.000148	-.000254	.202	-2.06	.850	-4.43	-.91
.002082	.000152	-.000250	.203	-2.08	.850	-3.11	-1.07
.002315	.000157	-.000248	.204	-2.08	.850	-2.05	-1.10
.002712	.000164	-.000248	.204	-2.05	.851	-.78	-1.24
.003018	.000173	-.000252	.205	-2.03	.850	-.06	-1.22
.003272	.000182	-.000247	.204	-2.10	.852	.61	-1.31
.003628	.000200	-.000253	.205	-2.08	.850	1.22	-1.40
.003760	.000209	-.000260	.206	-2.13	.848	1.44	-1.49
.002697	.000165	-.000256	.205	-2.09	.845	-.95	-1.27
.001813	.000137	-.000204	.203	-2.07	.844	-3.28	-1.07

TABLE III.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.002143	.000154	-.000256	.204	-.08	.856	-4.63	-1.02
.002365	.000155	-.000241	.204	-.03	.856	-3.46	-.98
.002686	.000164	-.000243	.205	.04	.854	-2.52	-1.10
.002979	.000174	-.000248	.206	.10	.851	-1.89	-1.23
.003264	.000183	-.000247	.205	-.01	.857	-1.10	-1.29
.003533	.000198	-.000253	.205	.05	.855	-.69	-1.29
.003727	.000210	-.000258	.205	-.04	.857	-.26	-1.34
.003529	.000196	-.000249	.205	-.08	.856	-.49	-1.39
.003283	.000184	-.000249	.205	-.14	.856	-.98	-1.16
.002904	.000170	-.000243	.205	-.19	.856	-1.71	-1.20
.002402	.000185	-.000286	.223	-2.07	.859	-2.97	-1.09
.002737	.000196	-.000306	.224	-2.06	.858	-2.15	-1.14
.003074	.000209	-.000311	.224	-2.11	.859	-1.14	-1.42
.003308	.000215	-.000305	.224	-2.03	.860	-.48	-1.26
.003630	.000238	-.000323	.224	-2.09	.860	.11	-1.35
.003799	.000250	-.000322	.225	-2.03	.860	.57	-1.30
.002828	.000200	-.000306	.224	-2.06	.860	-1.82	-1.29
.002166	.000187	-.000321	.222	-2.00	.858	-4.92	-.85
.002443	.000188	-.000304	.224	-.03	.855	-4.99	-.98
.002772	.000196	-.000303	.226	.04	.854	-3.79	-1.08
.003117	.000208	-.000308	.226	.10	.856	-2.96	-1.15
.003443	.000224	-.000315	.226	.16	.855	-2.22	-1.25
.003664	.000233	-.000300	.226	-.13	.856	-1.15	-1.29
.003929	.000257	-.000309	.227	-.08	.854	-.57	-1.23

TABLE III.- Concluded

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.002595	.000181	-.000265	.224	-.05	.851	-3.67	-.95
.002846	.000185	-.000251	.225	.00	.849	-2.72	-1.27
.003197	.000197	-.000255	.225	.07	.851	-1.88	-1.23
.003344	.000200	-.000247	.225	-.08	.852	-1.27	-1.34
.003744	.000229	-.000260	.225	-.09	.852	-.51	-1.33
.003889	.000240	-.000268	.225	-.06	.851	-.30	-1.27
.003321	.000195	-.000228	.225	-.16	.851	-1.02	-1.12
.003086	.000191	-.000246	.224	-.21	.851	-1.78	-1.08
.002858	.000187	-.000262	.224	-.26	.850	-2.59	-1.00
.002386	.000177	-.000248	.226	-2.02	.862	-2.48	-1.32
.002703	.000183	-.000251	.224	-2.10	.863	-1.29	-1.37
.003040	.000191	-.000250	.224	-2.03	.863	-.42	-1.41
.003337	.000203	-.000248	.225	-2.05	.861	.34	-1.43
.003688	.000226	-.000258	.225	-2.02	.862	1.01	-1.53
.003761	.000230	-.000251	.226	-2.02	.861	1.27	-1.48
.002667	.000179	-.000248	.224	-2.06	.863	-1.36	-1.24
.002079	.000165	-.000239	.223	-2.06	.863	-3.43	-1.20

TABLE IV.- FORWARD-FLIGHT PERFORMANCE OF ADVANCED BLADE

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.001221	.000066	-.000064	.102	-.18	.771	-.61	-.79
.001454	.000068	-.000071	.102	-.23	.772	.07	-1.05
.001847	.000071	-.000069	.103	-.23	.773	1.03	-1.01
.002159	.000077	-.000077	.103	-.25	.772	1.38	-1.04
.002426	.000083	-.000074	.103	-.31	.774	1.86	-1.17
.002712	.000090	-.000080	.103	-.33	.773	2.08	-1.09
.003037	.000100	-.000085	.103	-.45	.773	2.40	-1.19
.003319	.000111	-.000087	.102	-.51	.772	2.66	-1.25
.003597	.000123	-.000093	.102	-.39	.773	2.69	-1.18
.003917	.000137	-.000091	.102	-.46	.773	3.00	-1.18
.002693	.000089	-.000075	.102	-.35	.774	2.23	-1.09
.001799	.000069	-.000065	.102	-.21	.774	1.12	-1.00
.001848	.000070	-.000068	.102	2.29	.772	-.97	-.80
.002170	.000077	-.000074	.103	2.23	.772	-.52	-.93
.002491	.000083	-.000074	.103	2.17	.772	-.06	-.95
.002759	.000090	-.000075	.102	2.11	.773	.24	-.96
.003049	.000100	-.000089	.103	2.09	.771	.27	-.91
.003348	.000112	-.000096	.103	2.13	.774	.41	-.97
.003653	.000124	-.000097	.102	2.09	.775	.67	-.98
.003960	.000138	-.000096	.103	2.03	.773	.92	-1.03
.002667	.000088	-.000072	.103	2.18	.773	.16	-.96
.001899	.000071	-.000068	.102	2.24	.775	-.84	-.82
.001771	.000069	-.000069	.102	4.81	.777	-3.39	-.54
.002094	.000075	-.000072	.102	4.78	.777	-2.75	-.54
.002448	.000081	-.000070	.102	4.66	.777	-2.07	-.64
.002685	.000088	-.000077	.103	4.61	.777	-1.91	-.78
.003019	.000098	-.000086	.103	4.68	.779	-1.82	-.62
.003284	.000107	-.000089	.103	4.62	.779	-1.57	-.74
.003597	.000124	-.000117	.102	4.52	.777	-1.65	-.58
.003900	.000136	-.000104	.102	4.62	.777	-1.22	-.68
.002701	.000088	-.000078	.102	4.66	.779	-1.94	-.62
.001744	.000069	-.000069	.102	4.71	.778	-3.31	-.54

TABLE IV.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.001805	.000082	-.000125	.144	-1.17	.809	-.38	-.75
.002082	.000084	-.000122	.144	-1.13	.806	.45	-.89
.002340	.000086	-.000108	.143	-1.10	.806	1.15	-.81
.002712	.000094	-.000132	.143	-1.15	.807	1.38	-.99
.002974	.000102	-.000132	.143	-1.19	.808	1.81	-1.04
.003254	.000108	-.000130	.144	-1.25	.806	2.25	-1.15
.003626	.000119	-.000144	.143	-1.24	.807	2.47	-.94
.003852	.000125	-.000132	.143	-1.29	.807	2.95	-1.14
.002737	.000095	-.000133	.143	-1.13	.807	1.45	-.98
.001795	.000080	-.000122	.143	-1.12	.806	-.27	-.84
.001805	.000084	-.000124	.143	1.40	.805	-2.85	-.48
.002077	.000086	-.000118	.144	1.37	.806	-1.74	-.92
.002390	.000092	-.000134	.144	1.34	.805	-1.30	-.72
.002670	.000097	-.000136	.143	1.33	.806	-.78	-.90
.003008	.000105	-.000139	.144	1.39	.805	-.35	-.77
.003338	.000112	-.000137	.143	1.31	.807	.15	-.86
.003612	.000123	-.000144	.144	1.24	.805	.41	-.79
.003924	.000134	-.000143	.144	1.23	.806	.74	-.79
.004181	.000148	-.000152	.144	1.21	.807	.95	-.89
.002694	.000098	-.000138	.143	1.33	.807	-.76	-.73
.001821	.000083	-.000123	.143	1.39	.807	-2.73	-.43
.002554	.000094	-.000135	.144	3.86	.801	-3.17	-.52
.002747	.000098	-.000138	.144	3.87	.800	-2.86	-.67
.003042	.000105	-.000134	.143	3.84	.804	-2.30	-.73
.003323	.000113	-.000139	.144	3.88	.802	-2.06	-.61
.003696	.000124	-.000137	.144	3.87	.803	-1.53	-.75
.003949	.000136	-.000152	.144	3.77	.803	-1.30	-.80
.004251	.000147	-.000145	.144	3.86	.802	-.93	-.64
.002905	.000101	-.000137	.143	3.79	.803	-2.50	-.64
.002220	.000089	-.000132	.143	3.83	.804	-3.79	-.53

TABLE IV.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.002346	.000114	-.000194	.184	-1.57	.845	-.71	-1.23
.002641	.000121	-.000206	.184	-1.56	.845	-.04	-1.39
.002949	.000126	-.000204	.184	-1.58	.846	.74	-1.45
.003212	.000132	-.000204	.184	-1.57	.847	1.25	-1.43
.003561	.000140	-.000208	.184	-1.56	.847	1.73	-1.32
.003788	.000148	-.000207	.186	-1.65	.845	2.18	-1.34
.004132	.000162	-.000204	.185	-1.62	.847	2.79	-1.58
.003070	.000129	-.000206	.184	-1.56	.846	.96	-1.33
.002097	.000113	-.000204	.183	-1.53	.847	-1.79	-1.14
.002310	.000116	-.000190	.184	.41	.845	-2.64	-1.11
.002623	.000122	-.000195	.184	.48	.845	-1.83	-1.22
.002935	.000129	-.000203	.184	.45	.845	-1.19	-1.11
.003221	.000135	-.000202	.184	.48	.845	-.56	-1.28
.003521	.000143	-.000208	.184	.33	.846	.01	-1.36
.003833	.000152	-.000203	.184	.43	.847	.57	-1.44
.004135	.000167	-.000205	.185	.43	.845	1.06	-1.38
.003067	.000130	-.000199	.185	.35	.846	-.70	-1.22
.002106	.000116	-.000201	.184	.41	.844	-3.63	-.98
.002070	.000098	-.000120	.184	-1.51	.848	.01	-1.29
.002388	.000101	-.000125	.184	-1.57	.847	.83	-1.56
.002673	.000105	-.000122	.184	-1.54	.847	1.45	-1.36
.002874	.000109	-.000126	.184	-1.58	.848	1.79	-1.37
.003189	.000114	-.000125	.185	-1.56	.847	2.30	-1.55
.003460	.000122	-.000124	.185	-1.60	.847	2.72	-1.55
.003823	.000133	-.000125	.185	-1.56	.845	3.12	-1.57
.004131	.000147	-.000133	.185	-1.64	.844	3.53	-1.60
.003082	.000112	-.000123	.185	-1.57	.844	2.16	-1.41
.002255	.000100	-.000120	.185	-1.60	.844	.64	-1.28

TABLE VI.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.002357	.000105	-.000122	.185	.49	.844	-1.18	-1.14
.002707	.000110	-.000128	.185	.51	.844	-.46	-1.32
.002945	.000115	-.000128	.185	.45	.845	.03	-1.41
.003207	.000120	-.000132	.186	.39	.843	.49	-1.37
.003533	.000128	-.000129	.185	.48	.844	.92	-1.23
.003855	.000139	-.000135	.185	.46	.844	1.32	-1.36
.004109	.000150	-.000139	.185	.44	.843	1.65	-1.45
.003040	.000117	-.000125	.184	.41	.844	.36	-1.32
.002496	.000107	-.000125	.184	.36	.846	-.70	-1.42
.002398	.000104	-.000123	.185	1.92	.836	-2.17	-1.17
.002715	.000109	-.000132	.185	1.94	.837	-1.57	-1.31
.003054	.000114	-.000125	.185	1.91	.836	-.85	-1.29
.003291	.000120	-.000123	.185	1.93	.837	-.43	-1.39
.003576	.000128	-.000133	.185	1.84	.836	-.08	-1.31
.003867	.000139	-.000132	.185	1.95	.837	.28	-1.42
.003658	.000130	-.000127	.186	1.75	.835	.17	-1.41
.003672	.000130	-.000129	.186	1.87	.834	.08	-1.36
.003638	.000130	-.000131	.185	1.83	.835	.04	-1.38
.003960	.000139	-.000131	.185	1.91	.834	.42	-1.37
.002414	.000137	-.000254	.203	-2.10	.849	-1.72	-1.06
.002695	.000140	-.000251	.203	-2.03	.851	-.77	-1.28
.002935	.000144	-.000251	.203	-2.02	.851	-.09	-1.36
.003276	.000150	-.000249	.204	-1.96	.849	.66	-1.26
.003532	.000158	-.000259	.204	-2.10	.850	1.16	-1.33
.003895	.000170	-.000250	.204	-2.01	.850	1.89	-1.22
.003121	.000146	-.000247	.203	-2.10	.851	.51	-1.39
.002304	.000135	-.000254	.202	-2.07	.851	-2.16	-1.16

TABLE IV.- Continued

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.002420	.000141	-.000254	.204	-.09	.853	-3.43	-.84
.002669	.000143	-.000247	.204	-.03	.853	-2.47	-.89
.002972	.000150	-.000256	.205	-.02	.852	-1.76	-.98
.003273	.000157	-.000259	.205	-.00	.854	-1.08	-1.08
.003550	.000166	-.000262	.205	-.08	.854	-.47	-1.04
.003797	.000175	-.000259	.205	-.16	.853	.21	-1.26
.004190	.000196	-.000259	.205	-.05	.855	1.01	-1.17
.003393	.000157	-.000247	.205	-.13	.855	-.47	-1.20
.002086	.000135	-.000247	.203	-.10	.854	-4.60	-.64
.002326	.000136	-.000241	.204	1.92	.860	-5.10	-.71
.002616	.000141	-.000249	.205	1.97	.860	-4.25	-.88
.002975	.000147	-.000251	.206	2.04	.858	-3.31	-1.03
.003281	.000155	-.000254	.206	1.98	.858	-2.53	-1.00
.003532	.000163	-.000253	.206	1.96	.858	-1.92	-1.00
.003830	.000173	-.000254	.206	1.93	.857	-1.26	-.93
.003047	.000147	-.000246	.205	1.84	.858	-2.85	-.75
.002265	.000137	-.000255	.204	1.92	.858	-5.70	-.56
.002396	.000125	-.000199	.203	-2.04	.852	-.70	-1.22
.002675	.000130	-.000204	.203	-1.98	.851	-.01	-1.29
.002942	.000136	-.000212	.204	-2.01	.851	.52	-1.27
.003308	.000141	-.000207	.204	-1.99	.852	1.35	-1.32
.003524	.000147	-.000207	.204	-1.96	.853	1.70	-1.35
.003914	.000162	-.000204	.205	-2.03	.850	2.48	-1.30
.004104	.000175	-.000217	.205	-2.10	.851	2.82	-1.53
.003139	.000137	-.000208	.204	-2.00	.852	1.03	-1.25
.002391	.000124	-.000196	.203	-2.06	.852	-.57	-1.16

TABLE IV.- Concluded

CL	CQ	CD	MU	ALPF	MT	A1S	B1S
.002410	.000130	-.000206	.206	-.09	.850	-2.50	-.98
.002782	.000136	-.000209	.206	-.01	.850	-1.50	-1.07
.002969	.000137	-.000204	.206	.01	.851	-1.00	-1.20
.003334	.000147	-.000212	.205	-.05	.850	-.21	-1.15
.003623	.000153	-.000204	.205	.02	.850	.35	-1.03
.003884	.000168	-.000213	.205	-.10	.851	.88	-1.42
.004198	.000180	-.000210	.205	-.12	.851	1.48	-1.20
.003492	.000145	-.000191	.205	-.23	.851	.53	-1.21
.002079	.000126	-.000204	.203	-.03	.850	-3.79	-.74
.002430	.000128	-.000202	.205	1.96	.858	-4.09	-.88
.002677	.000130	-.000194	.205	2.00	.858	-3.20	-.94
.002961	.000137	-.000209	.206	1.96	.858	-2.66	-.97
.003190	.000142	-.000201	.206	1.96	.855	-2.04	-1.05
.003615	.000156	-.000212	.207	1.97	.853	-1.26	-.91
.003862	.000164	-.000212	.206	1.99	.854	-.82	-1.09
.003103	.000138	-.000201	.205	1.85	.854	-2.10	-.99
.002240	.000125	-.000201	.204	1.92	.855	-4.78	-.69
.003022	.000174	-.000301	.225	.12	.868	-2.77	-.77
.002687	.000169	-.000303	.224	.11	.870	-3.90	-.62
.002406	.000164	-.000300	.223	.09	.869	-4.91	-.66
.002143	.000158	-.000282	.223	.04	.869	-5.88	-.62
.003307	.000182	-.000305	.225	.27	.870	-2.04	-.98
.003544	.000189	-.000306	.225	.32	.871	-1.48	-.98
.003824	.000200	-.000303	.225	.40	.872	-.77	-.89
.003156	.000180	-.000312	.224	.19	.870	-2.59	-.71

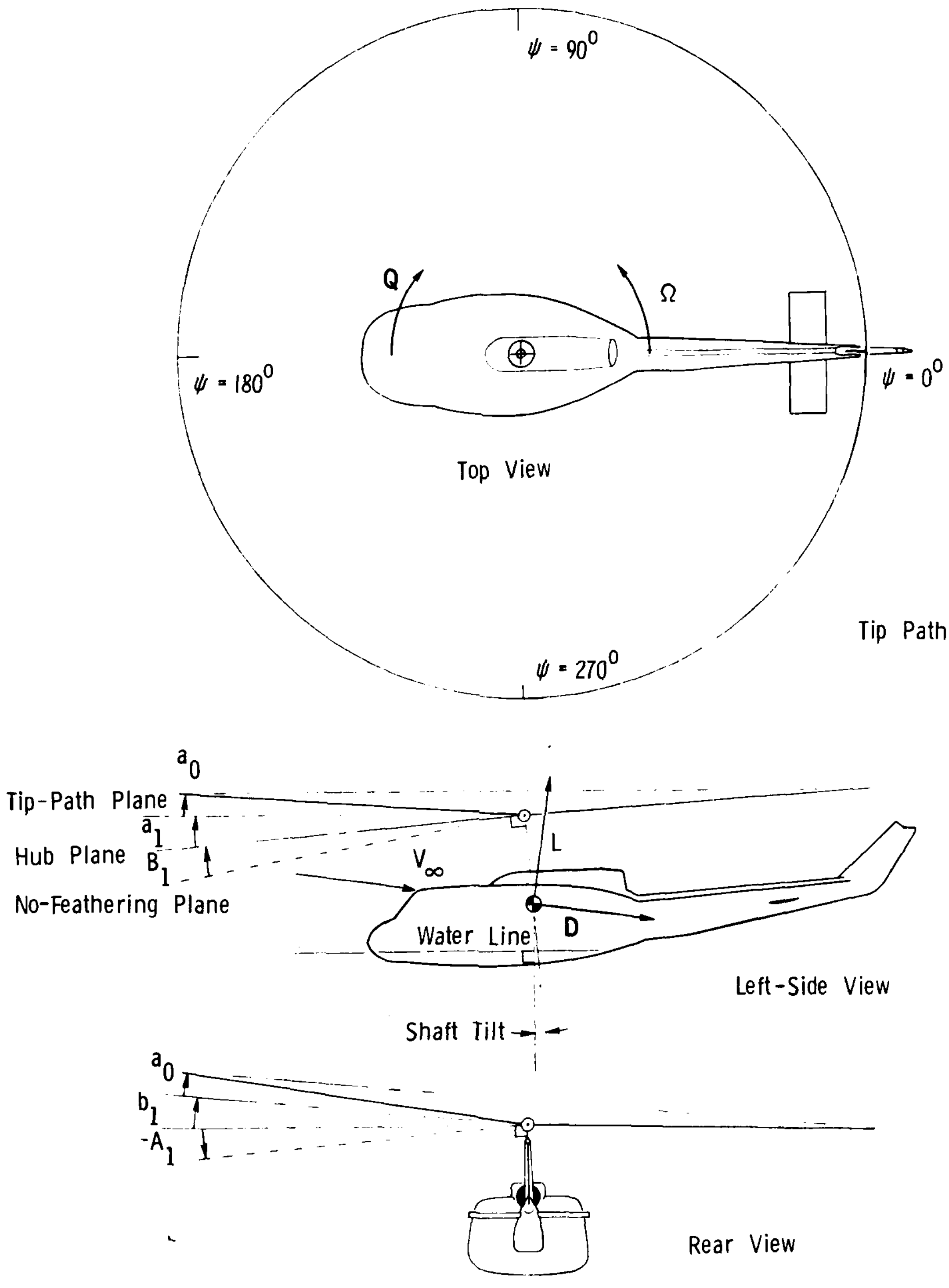
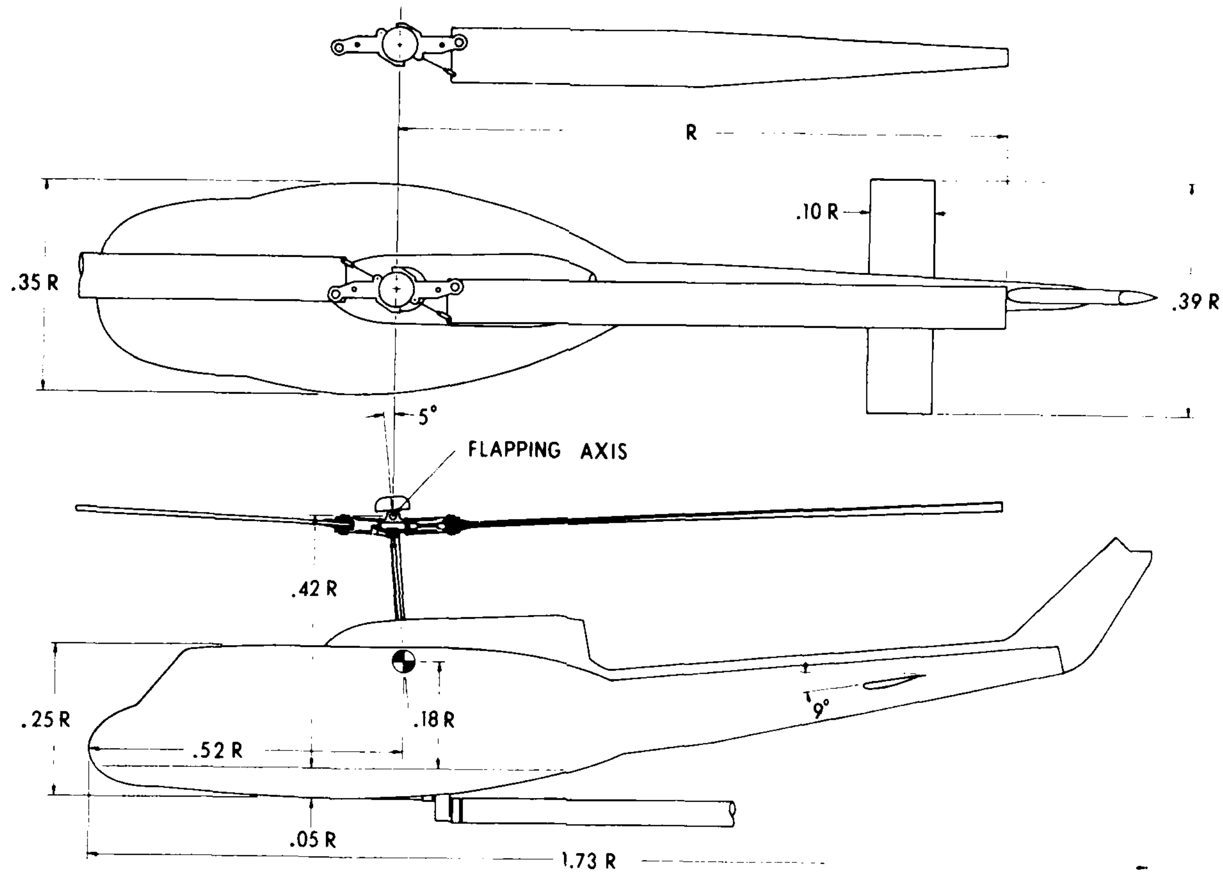
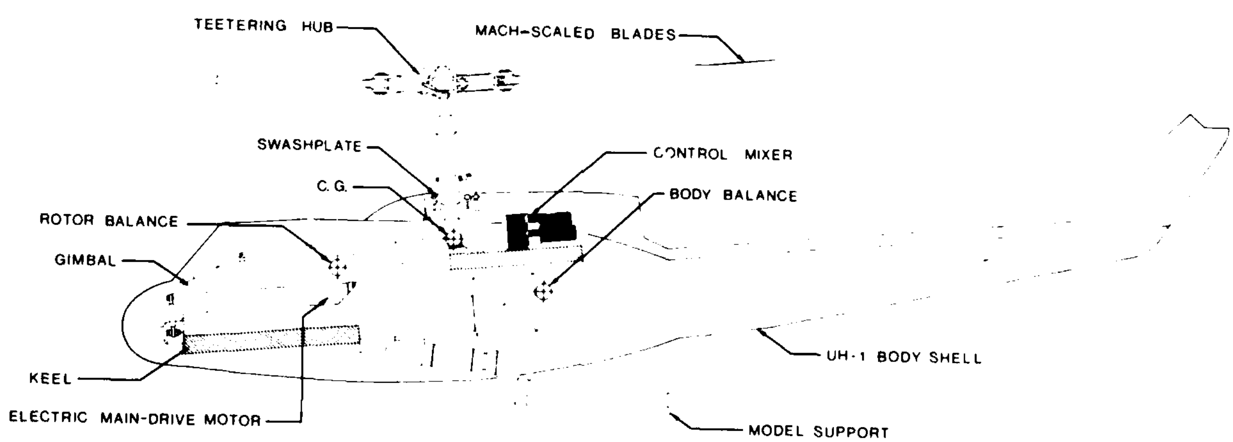


Figure 1.- Conventions for directed quantities.



(a) Sketch.



(b) Internal components.

Figure 2.- Model of UH-1 helicopter.

(c) Mounted in Langley 4- by 7-Meter Tunnel. L-80-2511

Figure 2.- Concluded.

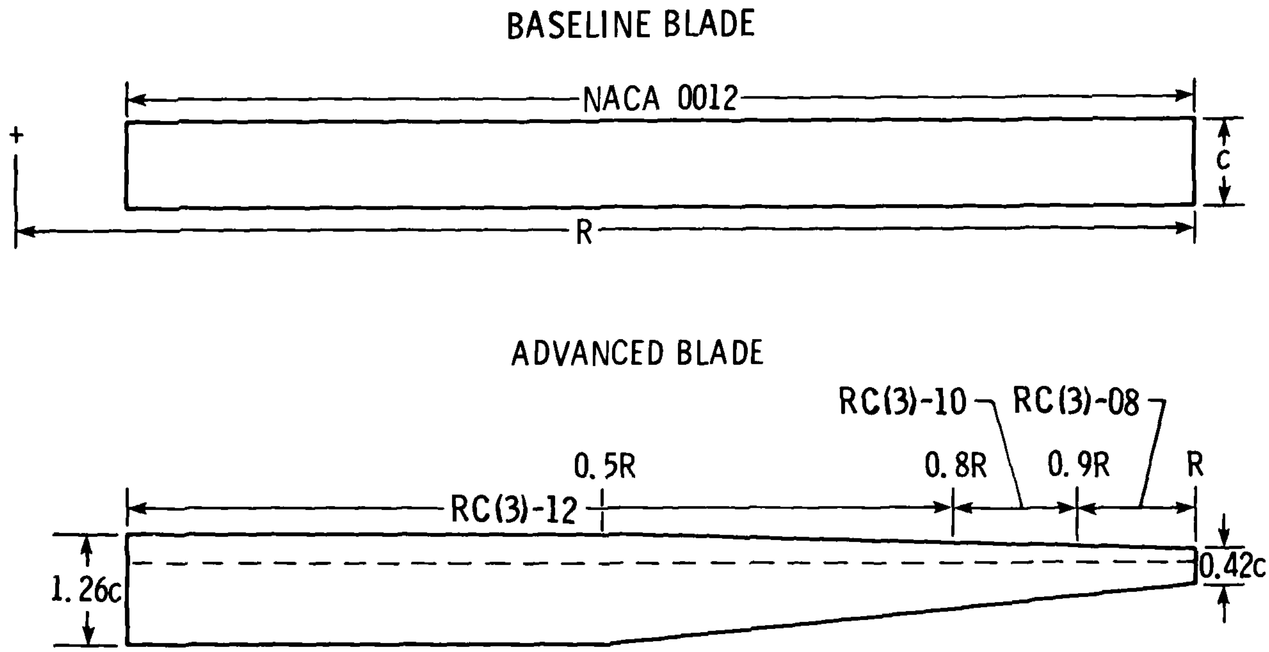


Figure 3.- Blade geometries.

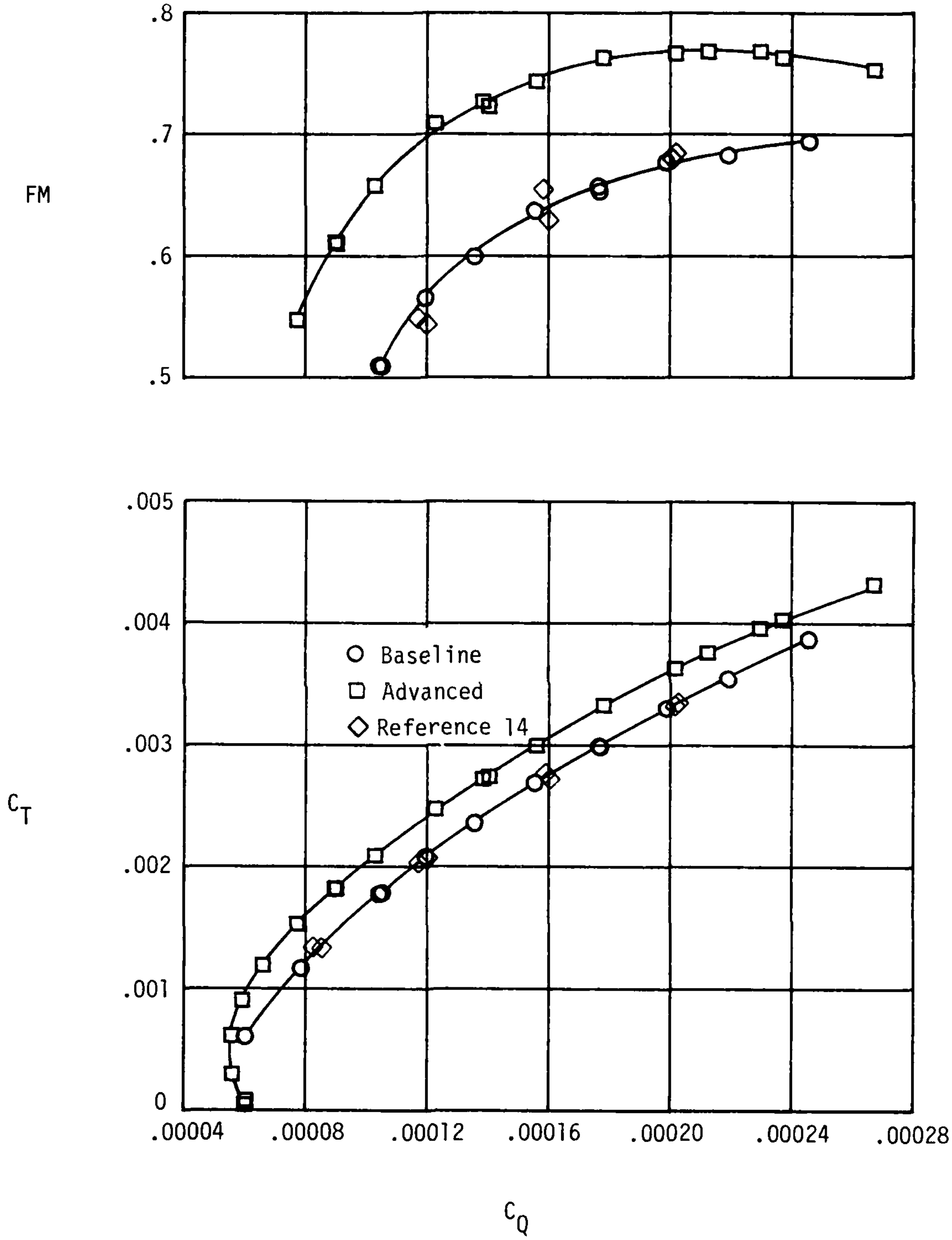


Figure 4.- Hover performance of rotor-blade sets out of ground effect.

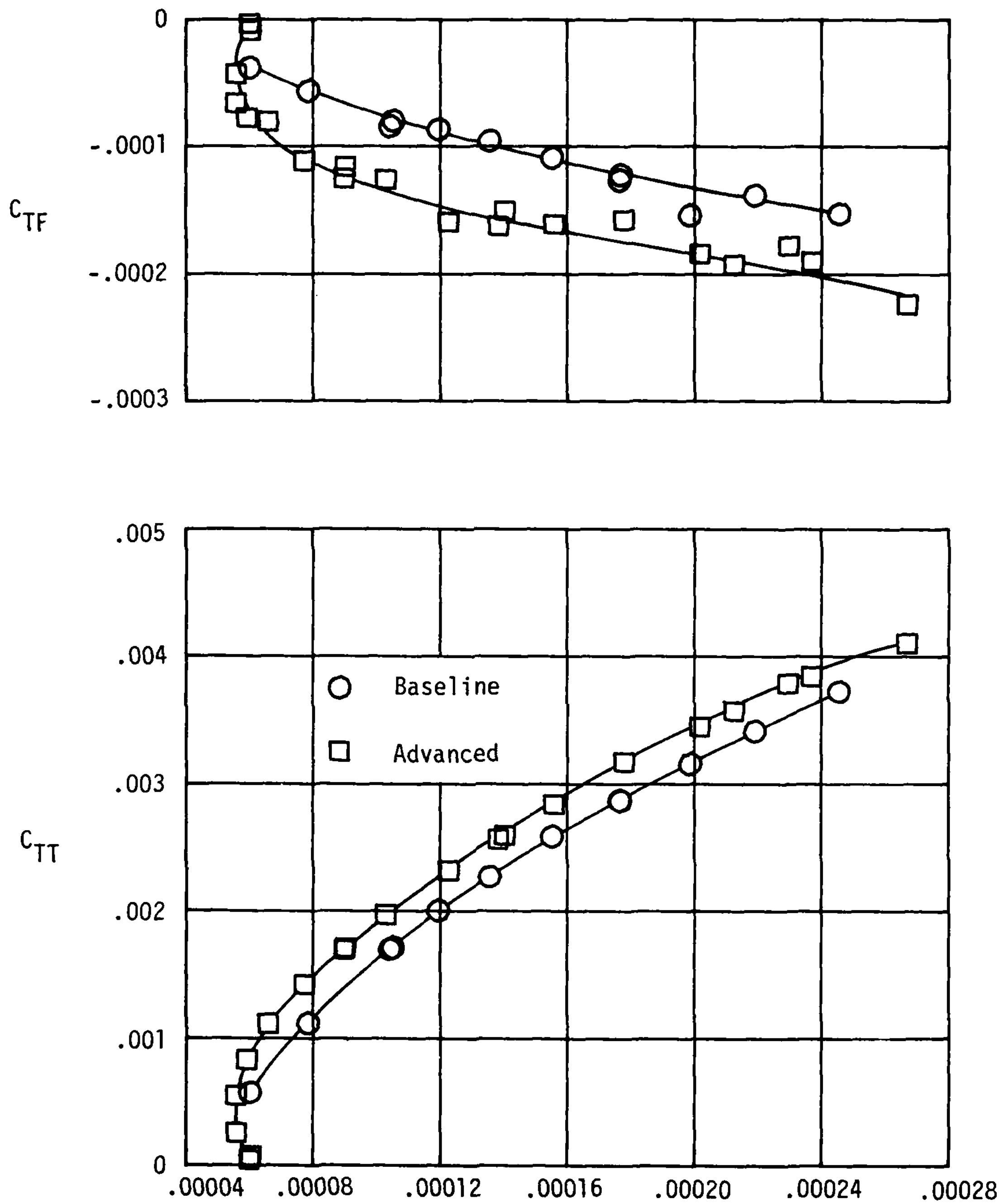


Figure 5.- Comparison of net hover performance of rotor-blade sets out of ground effect.

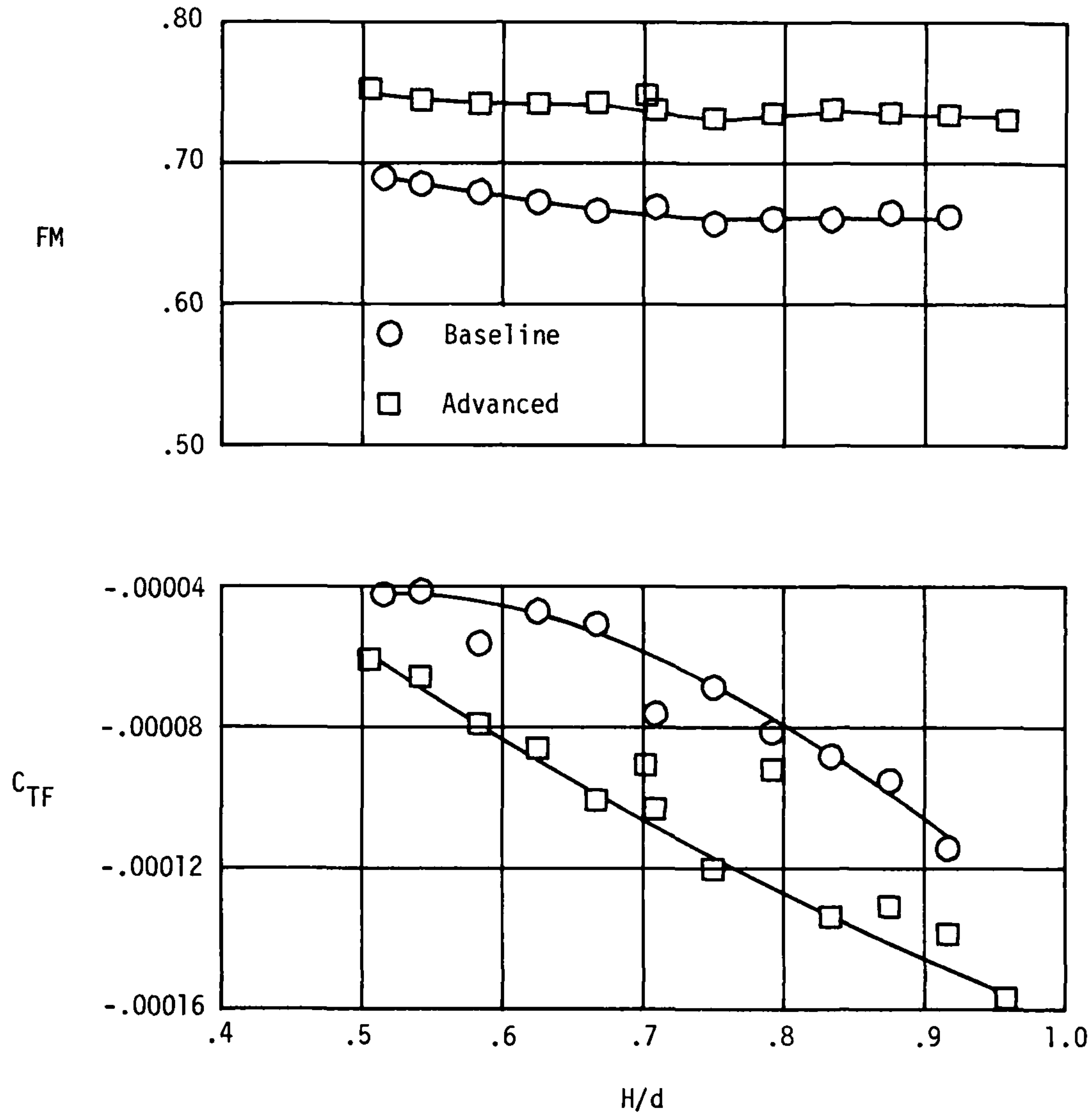
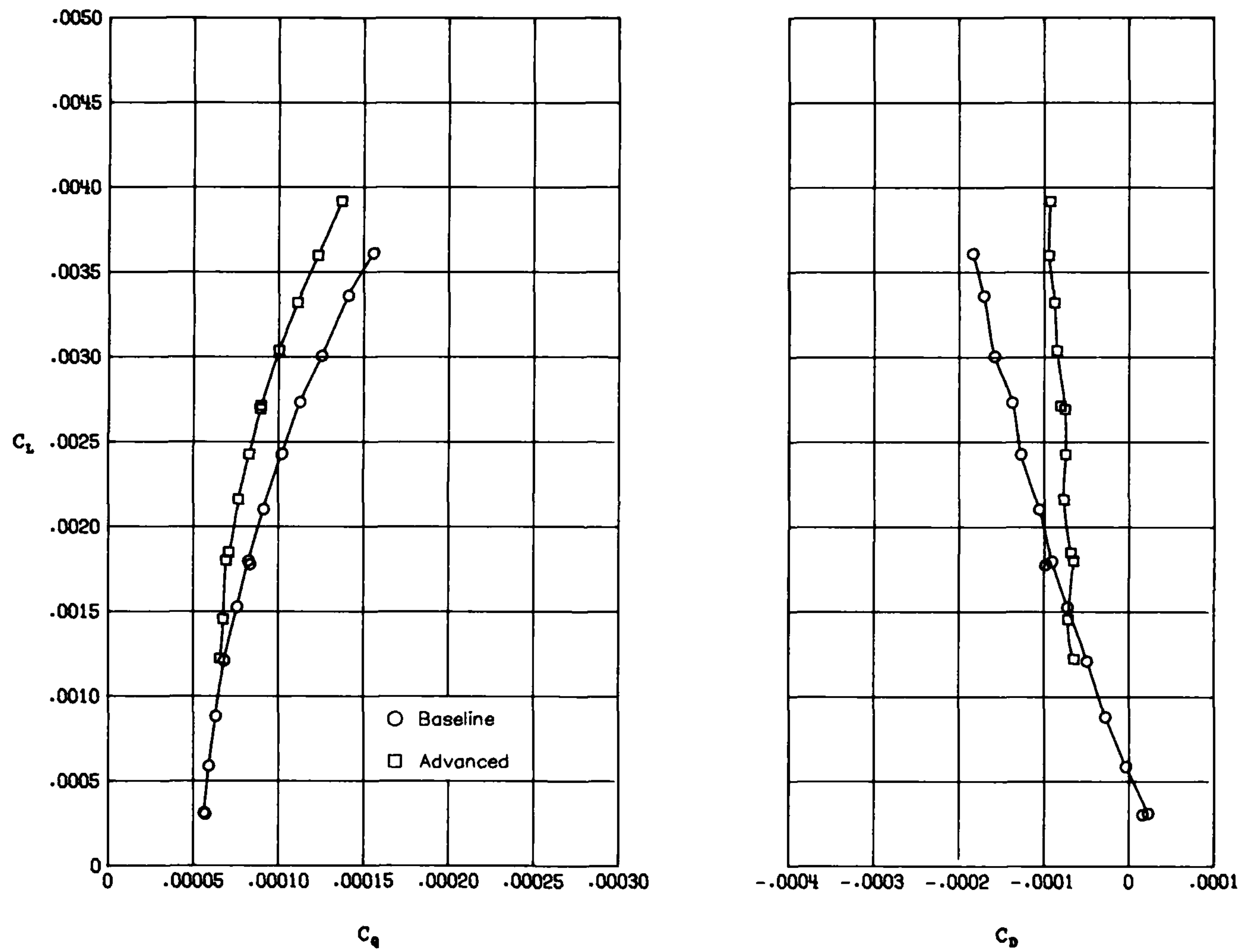
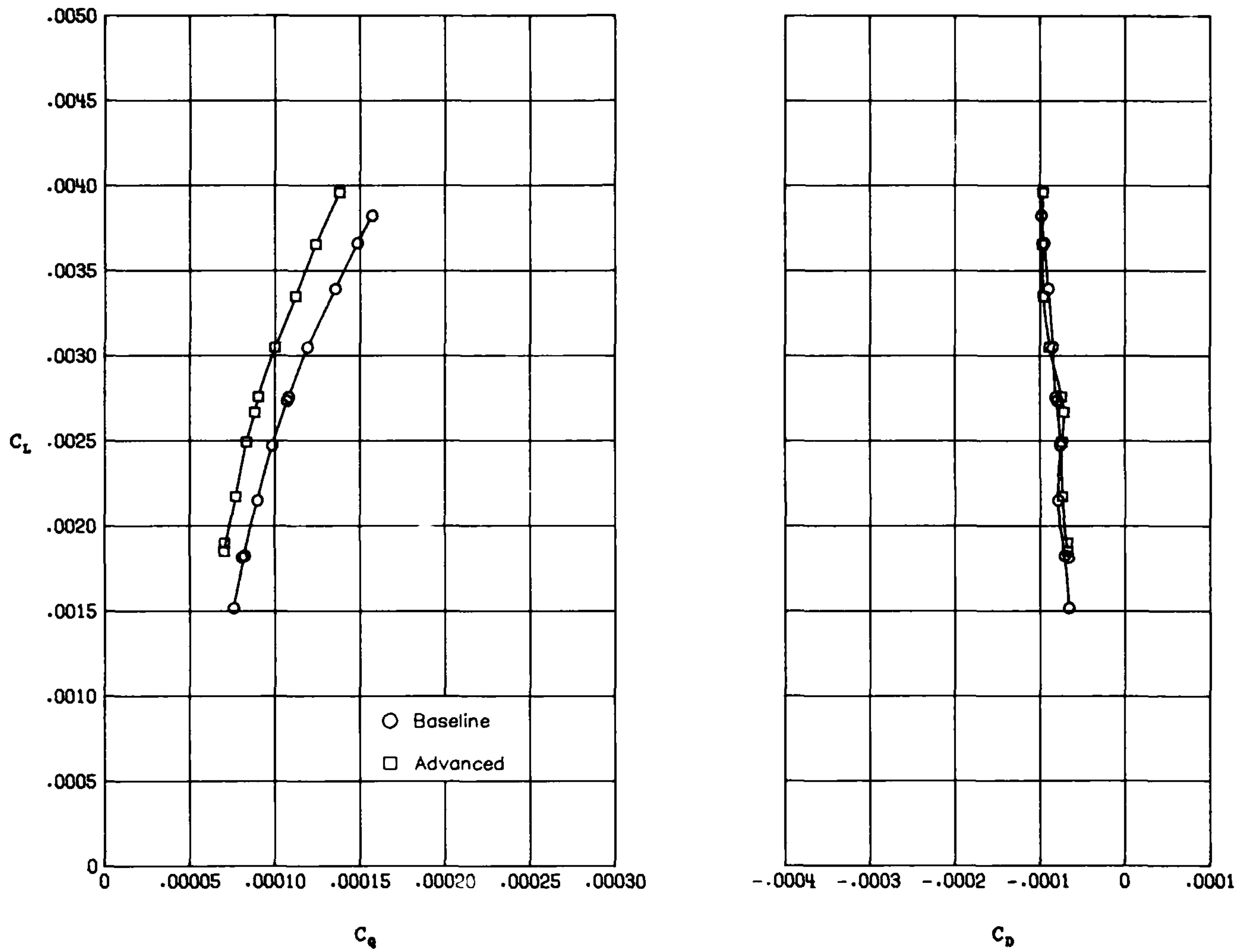


Figure 6.- Comparison of ground proximity effects.



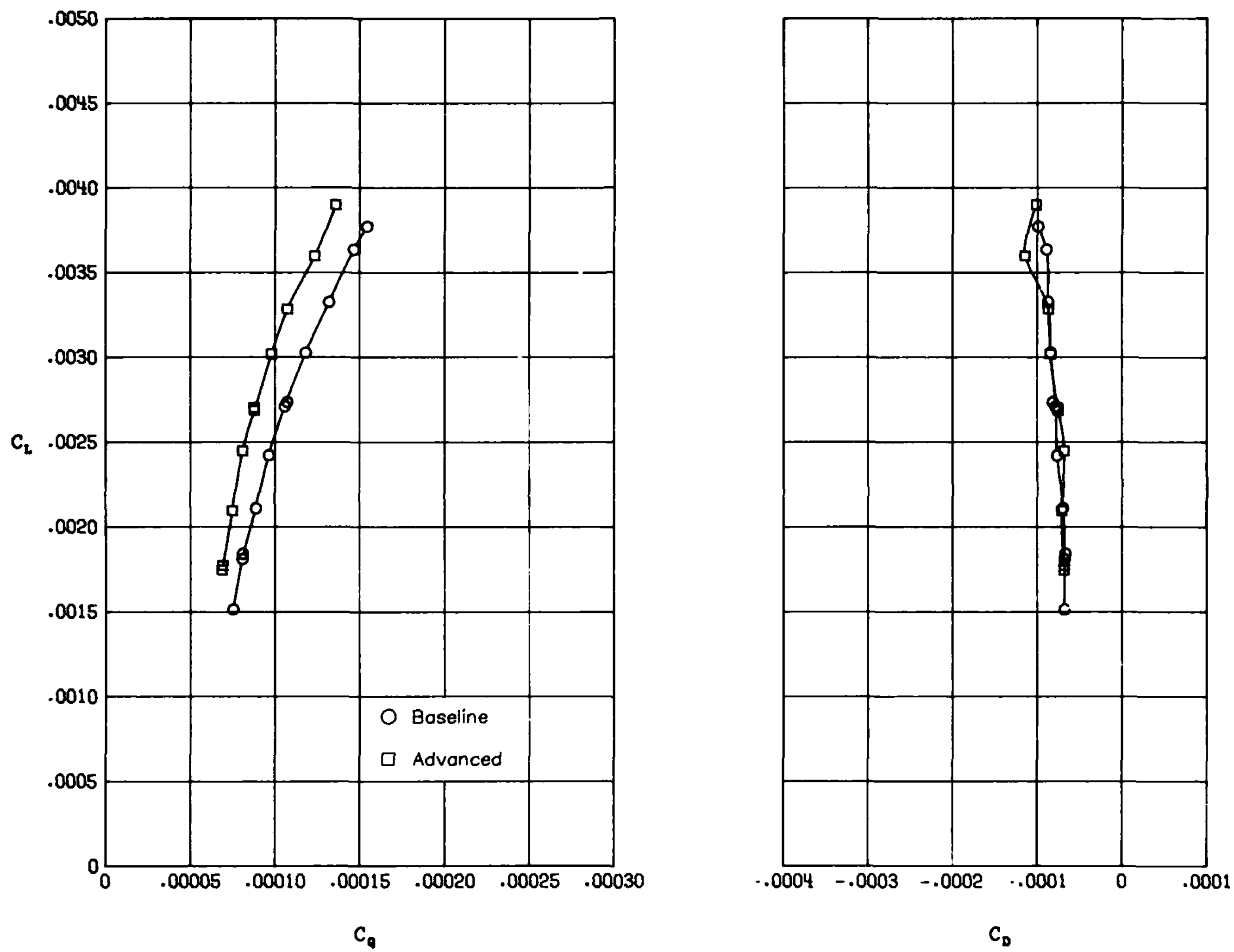
(a) $\alpha_f \cong 0.0$, $\mu = 0.10$.

Figure 7.- Comparison of forward-flight performance. (See table II.)



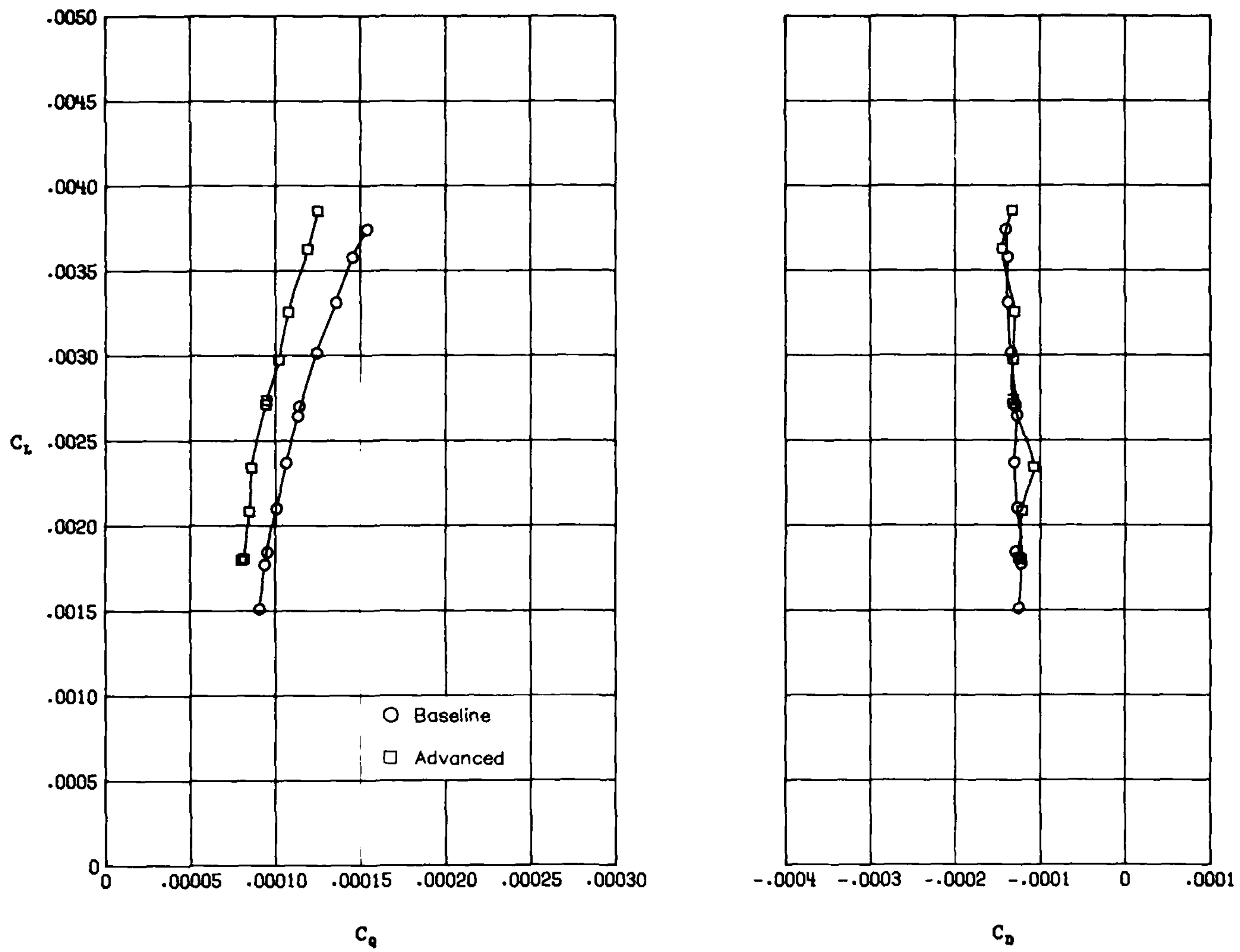
(b) $\alpha_f = 2.2$, $\mu = 0.10$.

Figure 7.- Continued.



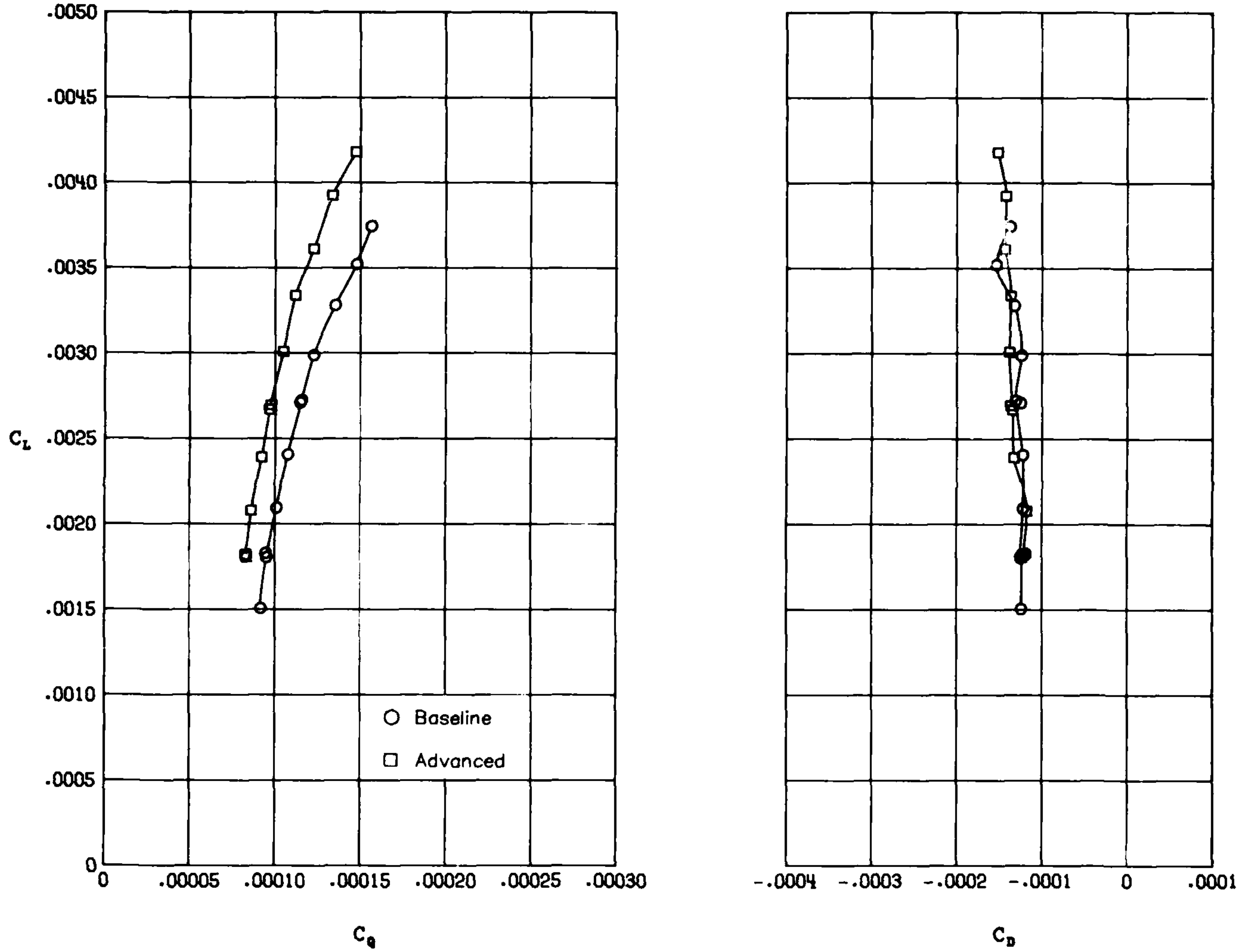
(c) $\alpha_f \cong 4.6$, $\mu = 0.10$.

Figure 7.- Continued.



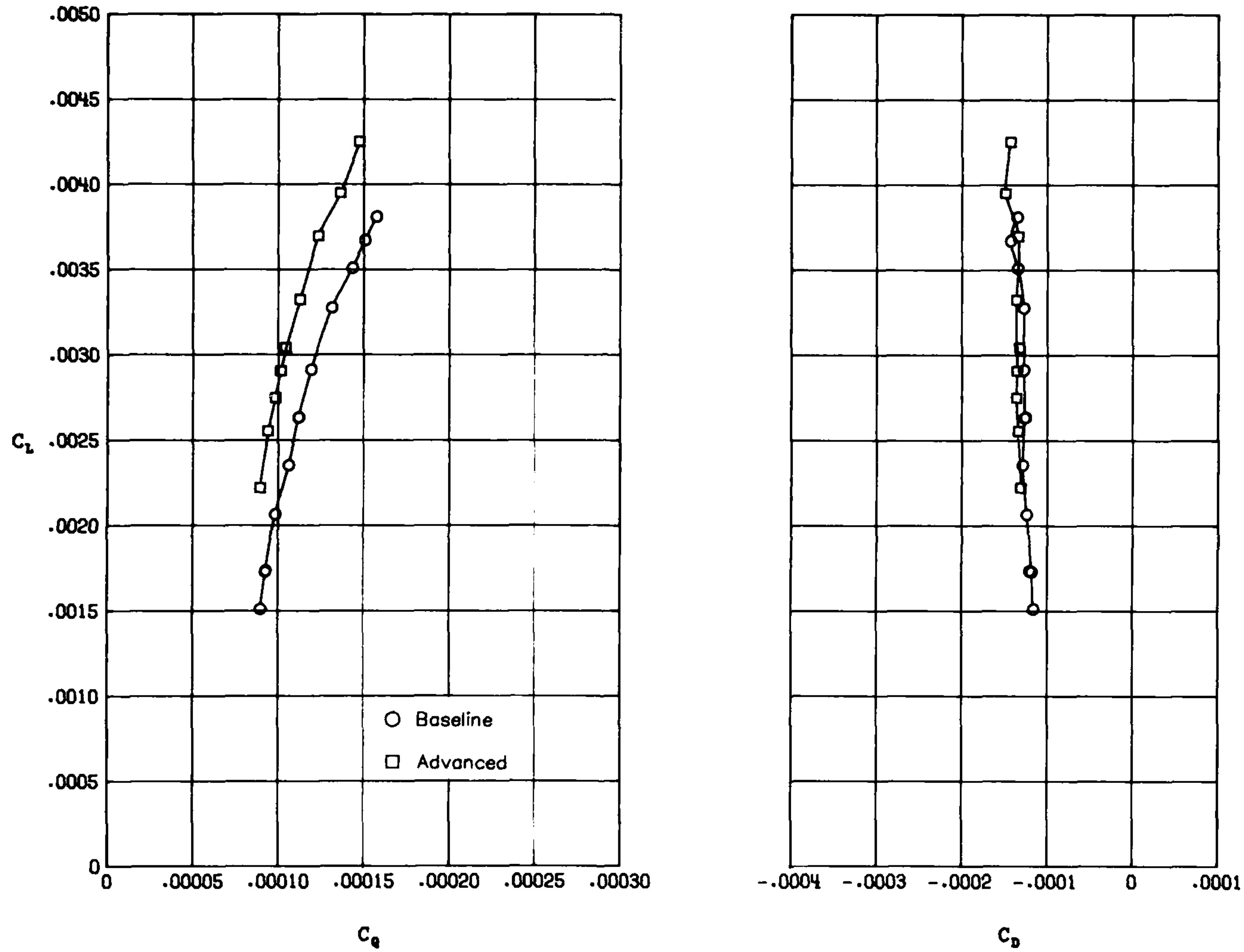
(d) $\alpha_f \cong -1.1$, $\mu = 0.14$.

Figure 7.- Continued.



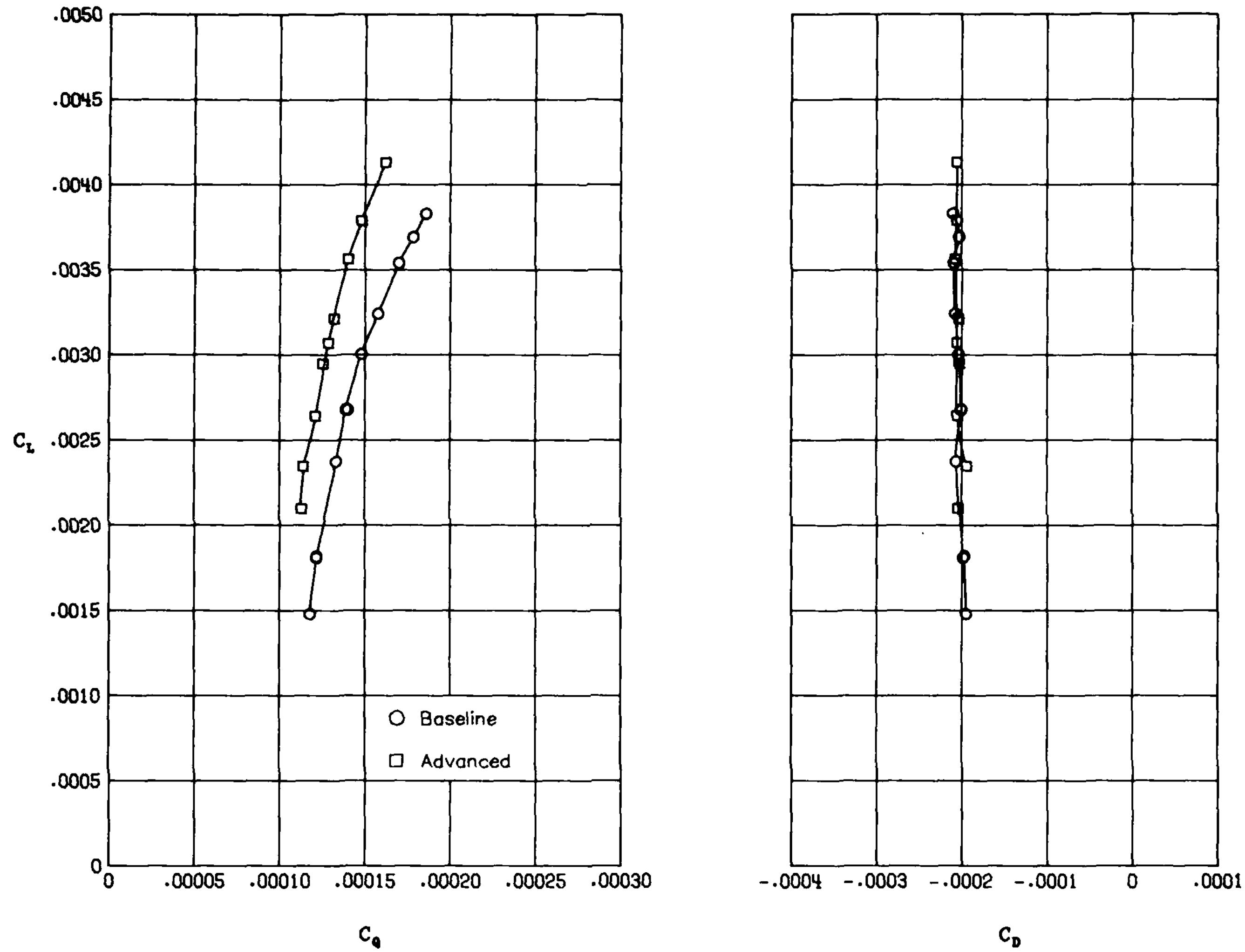
(e) $\alpha_f = 1.3$, $\mu = 0.14$.

Figure 7.- Continued.



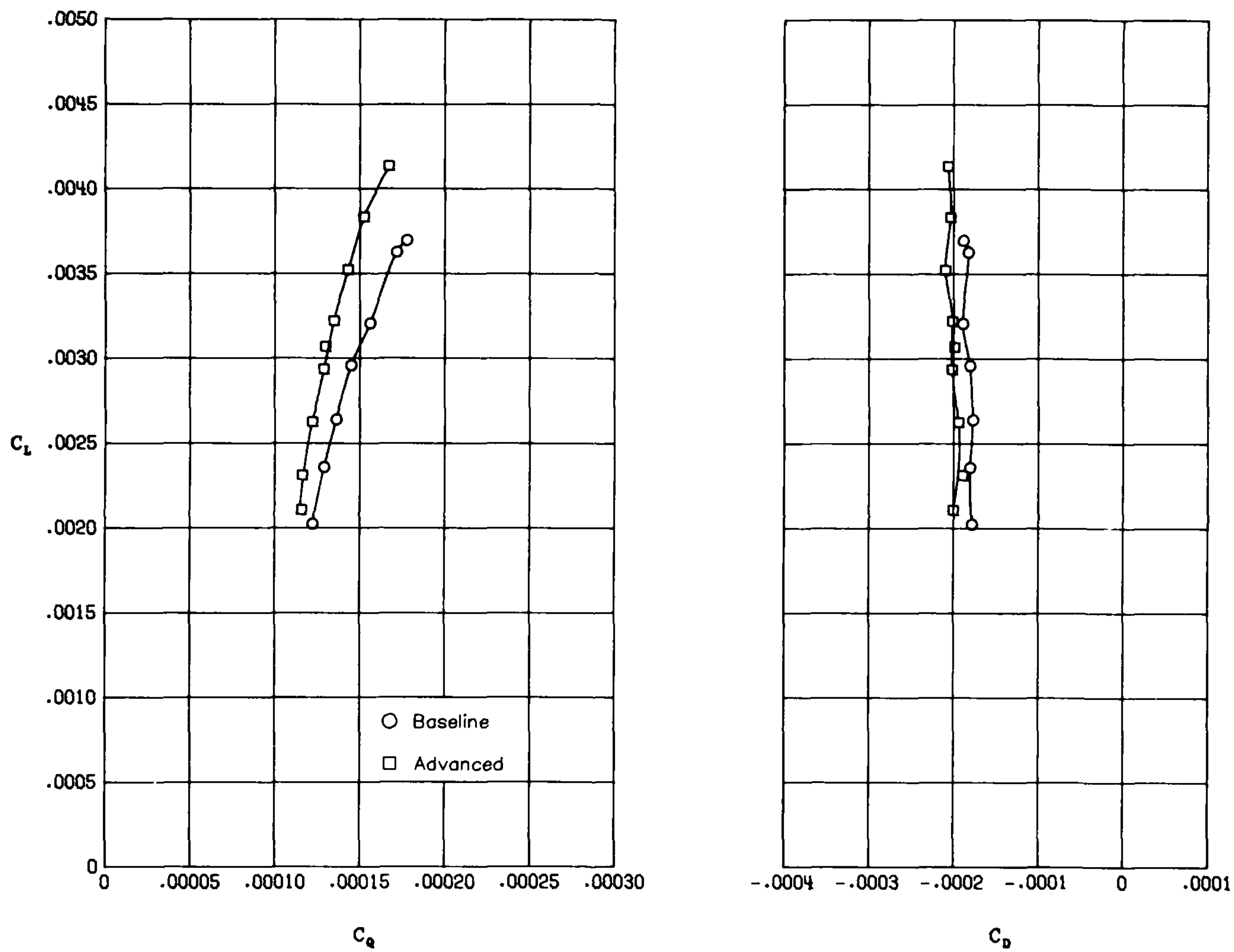
(f) $\alpha_f \cong 3.8$, $\mu = 0.14$.

Figure 7.- Continued.



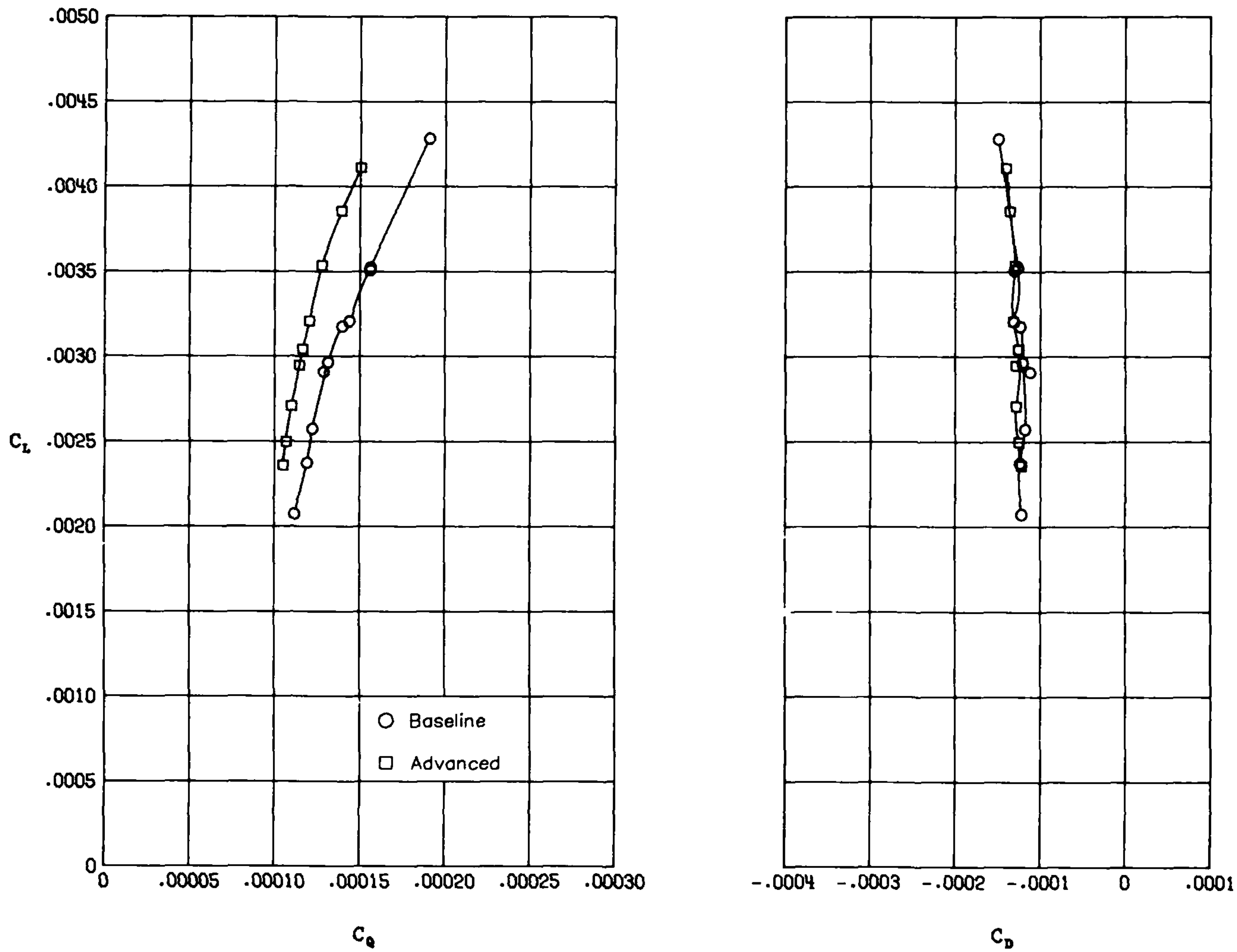
(g) $\alpha_f = -1.6$, $\mu = 0.18$.

Figure 7.- Continued.



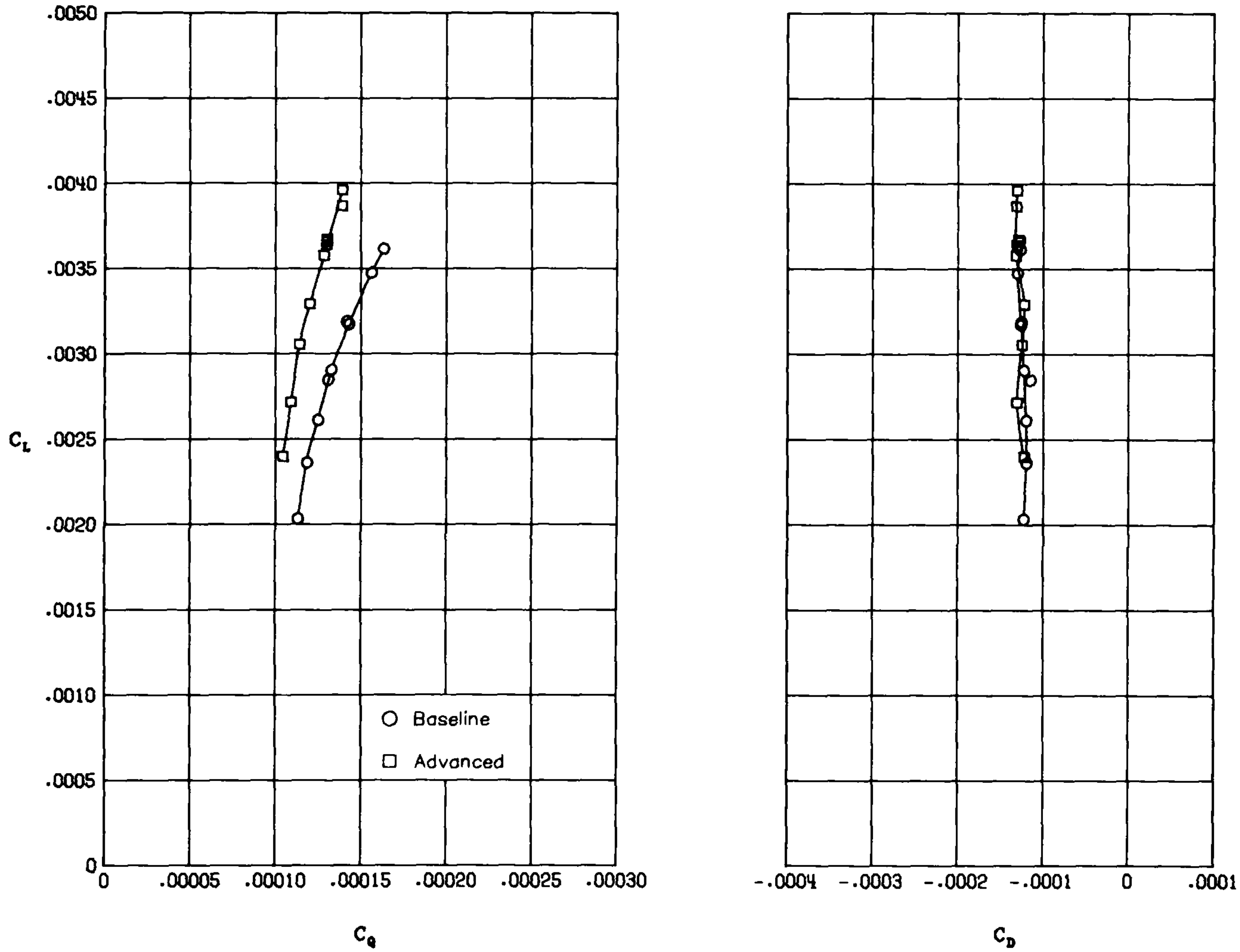
(h) $\alpha_f = 0.4$, $\mu = 0.18$.

Figure 7.- Continued.



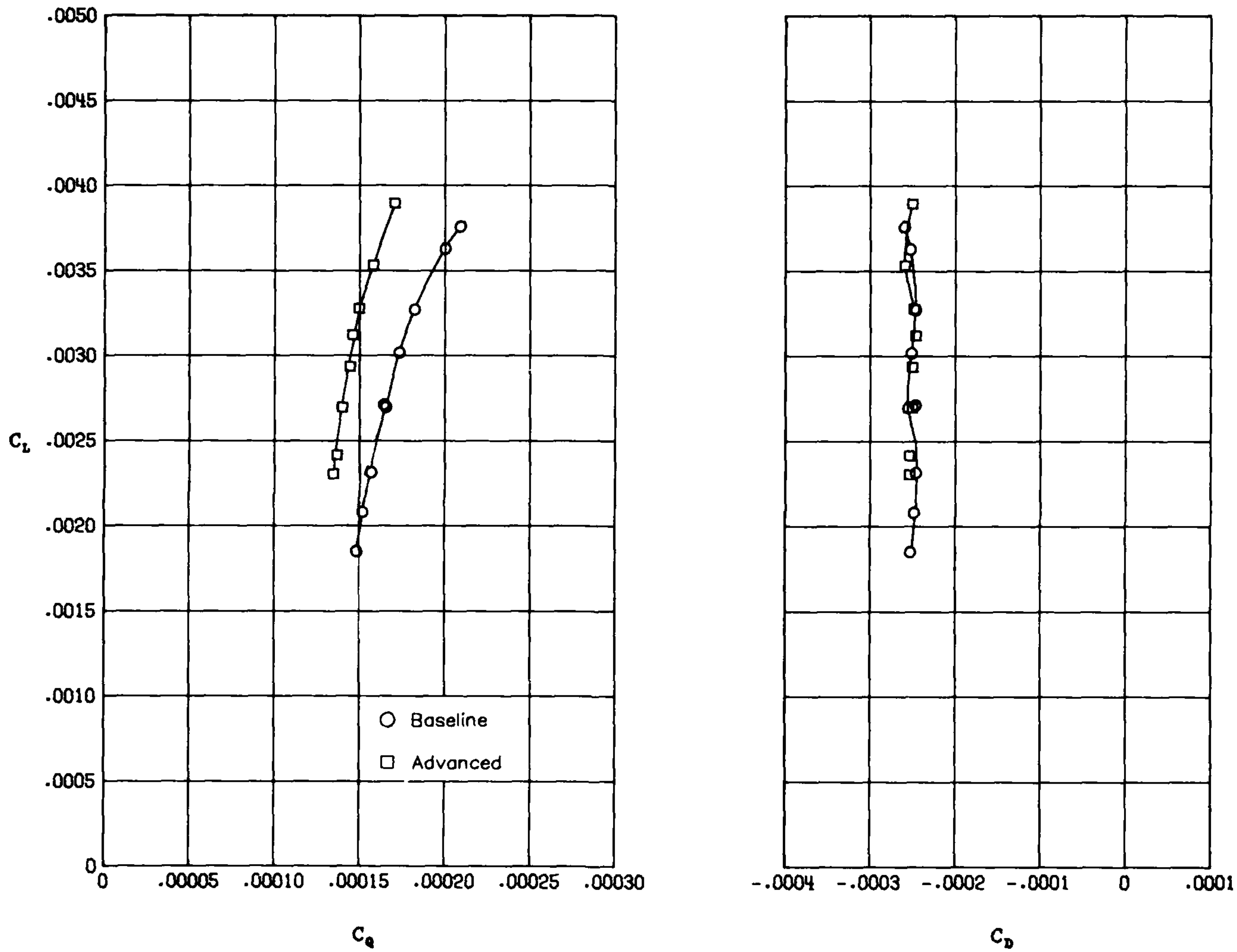
(i) $\alpha_f = 0.4$, $\mu \cong 0.18$.

Figure 7.- Continued.



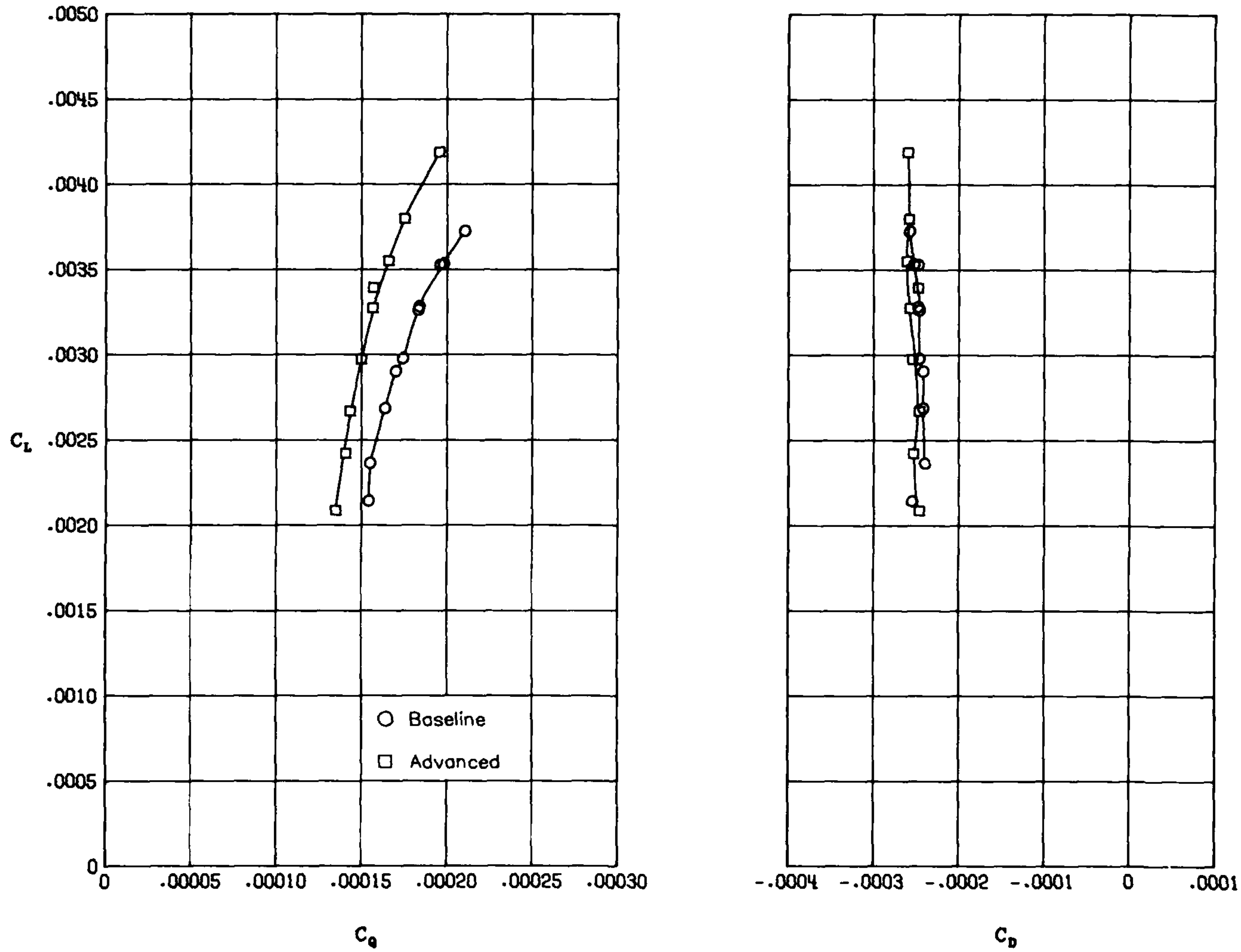
(j) $\alpha_f \cong 2.0$, $\mu \cong 0.18$.

Figure 7.- Continued.



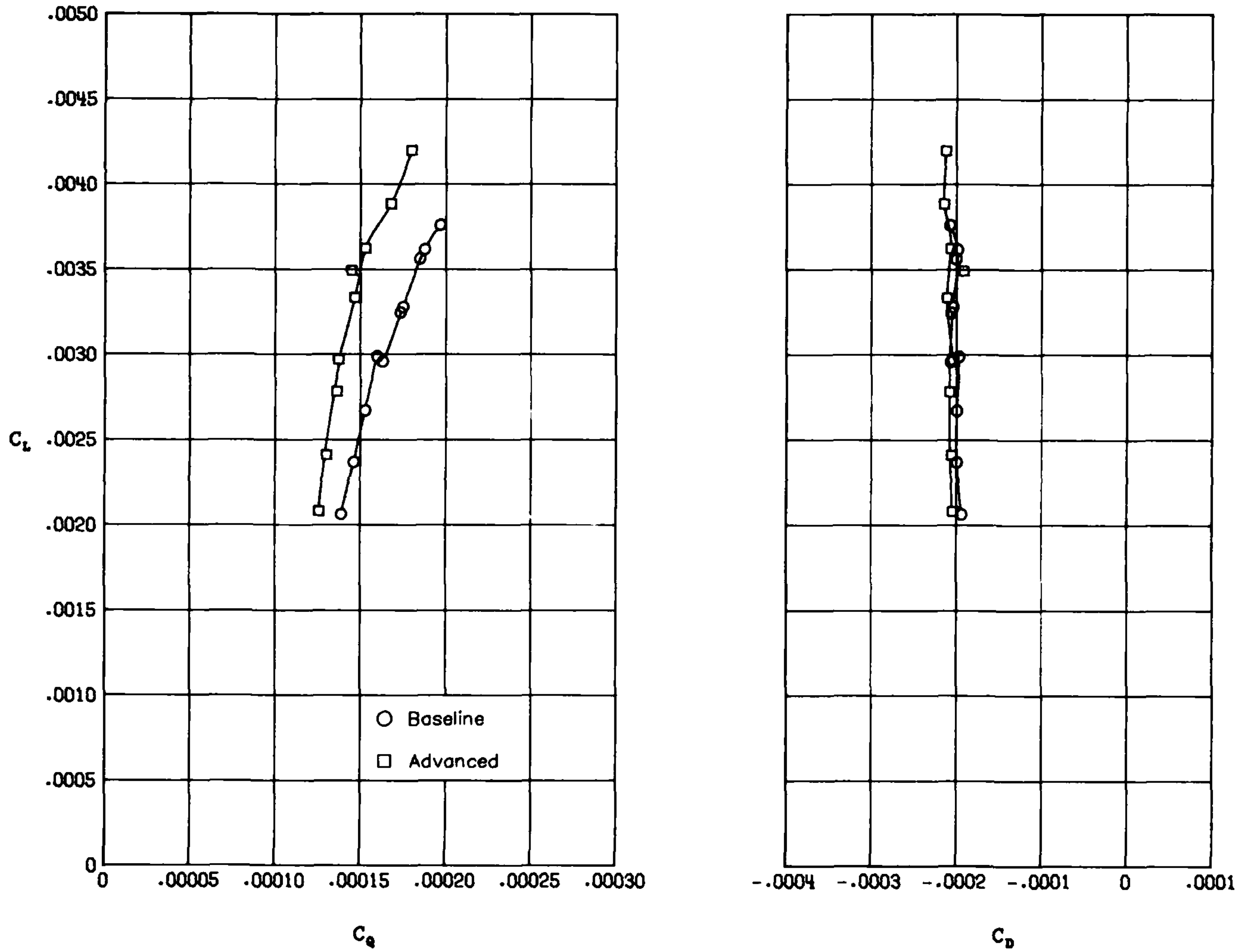
(k) $\alpha_f \cong -2.0$, $\mu = 0.20$.

Figure 7.- Continued.



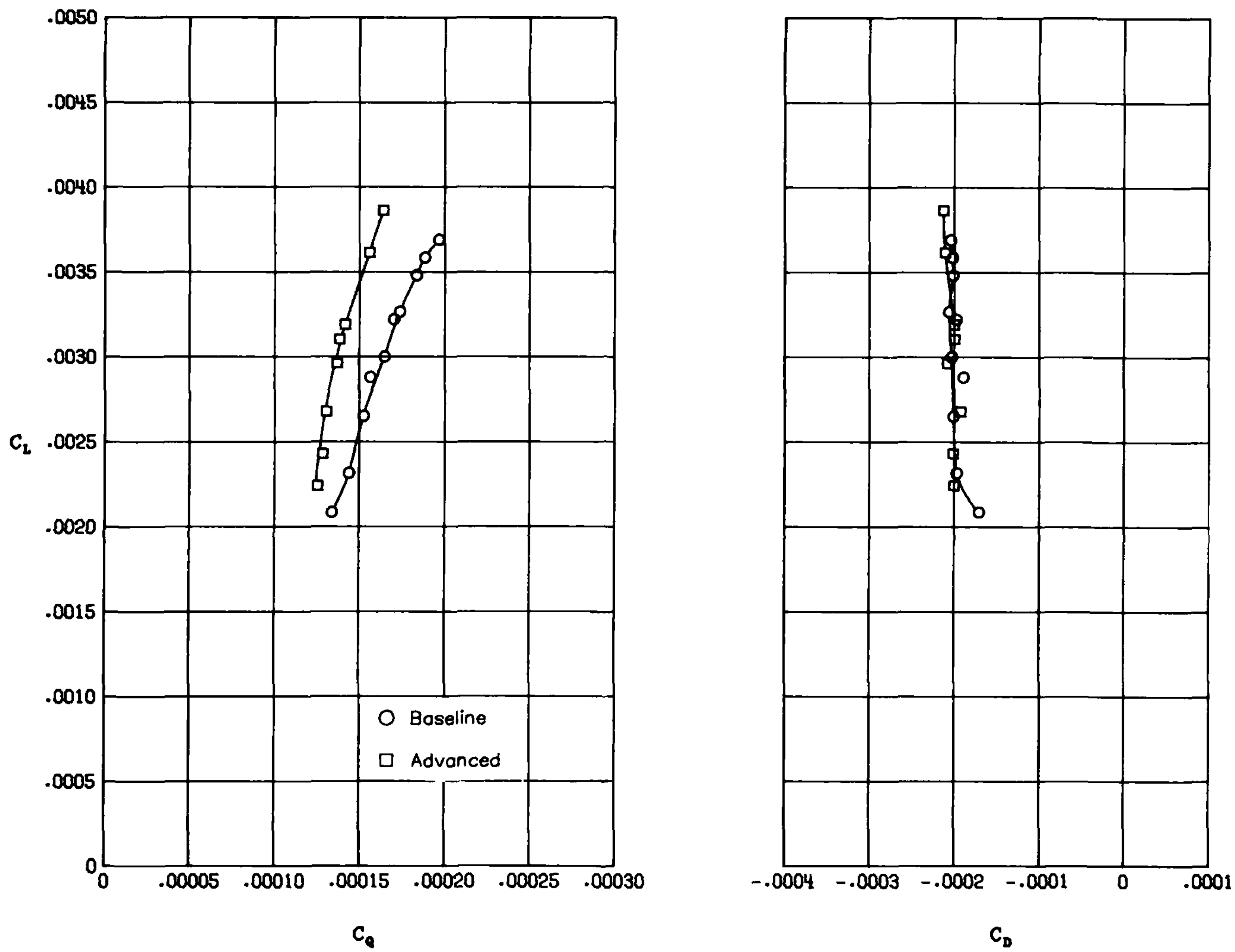
(1) $\alpha_f \cong 0.0$, $\mu = 0.20$.

Figure 7.- Continued.



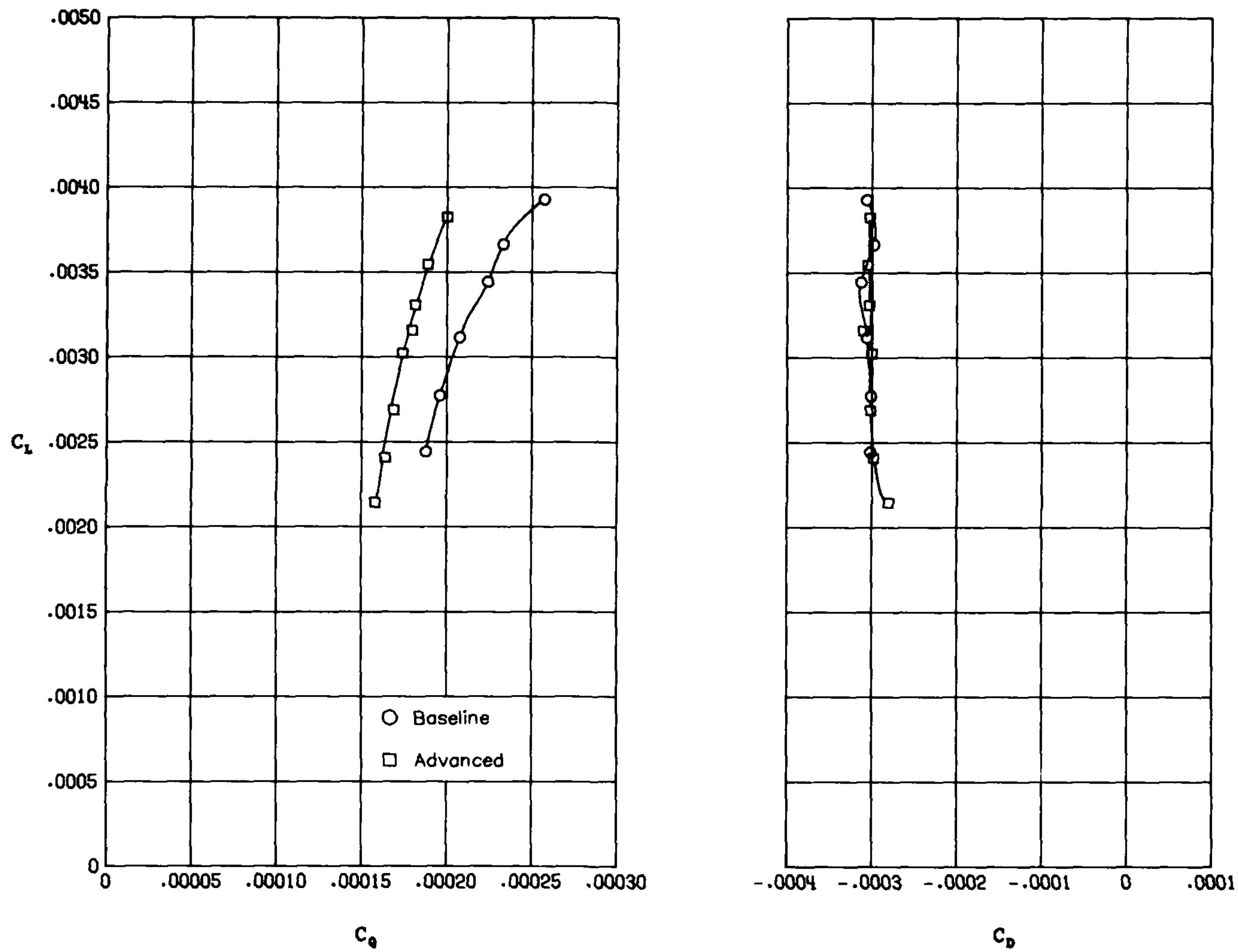
(m) $\alpha_f \cong 0.0$, $\mu \cong 0.20$.

Figure 7.- Continued.



(n) $\alpha_f \cong 2.0$, $\mu \cong 0.20$.

Figure 7.- Continued.



(c) $\alpha_f \cong 0.2$, $\mu \cong 0.22$.

Figure 7.- Concluded.

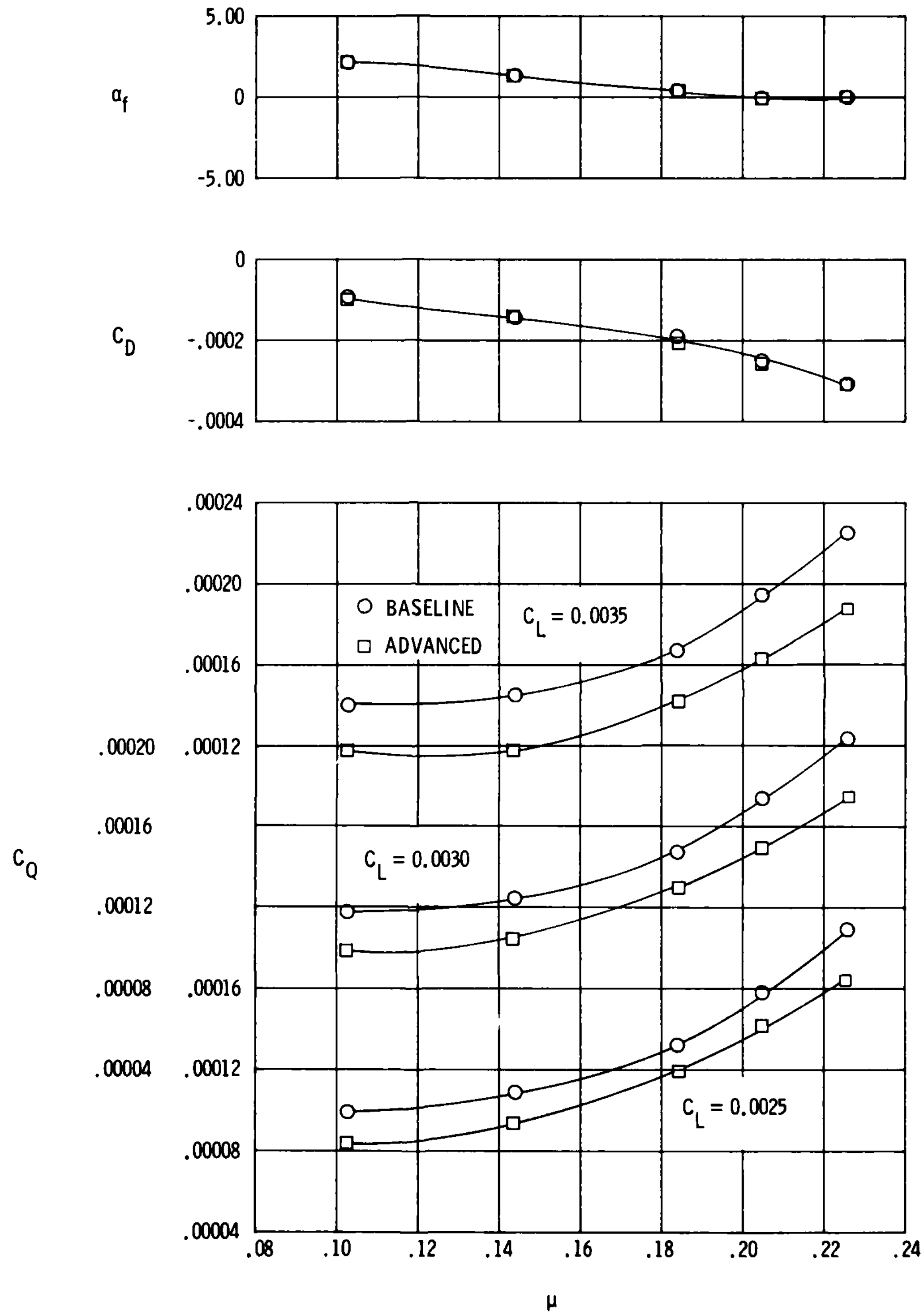


Figure 8.- Performance comparison of advanced and baseline rotor systems at several advance ratios.

1. Report No. NASA TM-83274 AVRADCOM TR 82-B-3	2. Government Accession No.	3. Recipient's Catalog No

4. Title and Subtitle
PERFORMANCE TESTING OF A MAIN ROTOR SYSTEM FOR A UTILITY HELICOPTER AT 1/4 SCALE

5. Report Date
April 1982

6. Performing Organization Code
505-42-23-01

7. Author(s)
John D. Berry

8. Performing Organization Report No
L-15015

9. Performing Organization Name and Address
Structures Laboratory
AVRADCOM Research and Technology Laboratories
NASA Langley Research Center
Hampton, VA 23665

10. Work Unit No.

11. Contract or Grant No

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546
and
U.S. Army Aviation Research and Development Command
St. Louis, MO 63166

13. Type of Report and Period Covered
Technical Memorandum

14. Army Project No.
1L161102AH45

15. Supplementary Notes
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16. Abstract
Two rotor systems for the UH-1 helicopter were tested at 1/4 scale in hover and forward flight. The "baseline" system was a dynamically scaled model of the current rotor system, while the other system was designed for "advanced" performance. In hover out of ground effect, the advanced rotor system showed improvements up to 10 percent in the figure of merit and improvements in thrust up to 7 percent. In forward flight, the advanced rotor system demonstrated reductions in required torque throughout the range of conditions tested, with reductions up to 17 percent occurring at the higher advance ratios and higher lift values tested.

17. Key Words (Suggested by Author(s))
UH-1 helicopter
Rotor aerodynamics
Performance
Hovering
Wind tunnel tests
Horizontal flight
Mach scaled
Ground effect

18. Distribution Statement
Unclassified - Unlimited
Subject Category 05

19. Security Classif (of this report)	20. Security Classif (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	49	A03

DATE
ILMED
-8